CHAPTER 3

Types of Reuse Applications

3.1 Introduction

While Chapter 2 provides a discussion of the key elements of water reuse common to most reuse projects (i.e., supply and demand, treatment requirements, storage, distribution), this chapter provides information specific to the major types of reuse applications:

- Urban
- Industrial
- Agricultural
- Recreational
- Habitat restoration/enhancement
- Groundwater recharge
- Augmentation of potable supplies

Quantity and quality requirements are considered for each reuse application, as well as any special considerations necessary when reclaimed water is substituted for traditional sources of water. A brief discussion of potable reuse is also presented. Case studies of reuse applications are provided in Section 3.8.

3.2 Urban Reuse

Urban reuse systems provide reclaimed water for various nonpotable purposes within an urban area, including:

- Irrigation of public parks and recreation centers, athletic fields, school yards and playing fields, highway medians and shoulders, and landscaped areas surrounding public buildings and facilities.
- Irrigation of the landscaped areas of single-family and multi-family residences, general washdown, and other maintenance activities.
- Irrigation of landscaped areas surrounding commercial, office, and industrial developments.
- Irrigation of golf courses.
- Commercial uses such as vehicle washing facilities, window washing, mixing water for pesticides, herbicides, and liquid fertilizers.
- Ornamental landscape uses and decorative water features, such as fountains, reflecting pools and waterfalls.
- Dust control and concrete production on construction projects.
- Fire protection.
- Toilet and urinal flushing in commercial and industrial buildings.

Urban reuse can include systems serving large users, such as parks, playgrounds, athletic fields, highway medians, golf courses, and recreational facilities; major water-using industries or industrial complexes; and a comprehensive combination of residential, industrial, and commercial properties through "dual distribution systems."

In dual distribution systems, the reclaimed water is delivered to the customers by a parallel network of distribution mains separate from the community's potable water distribution system. The reclaimed water distribution system essentially becomes a community's third water utility (wastewater, potable water, reclaimed water) and is operated, maintained, and managed in a manner similar to the potable water system. The oldest municipal dual distribution in the U.S., in St. Petersburg, Florida, has been in operation since 1977. The system provides reclaimed water for a mix of residential properties, commercial developments, industrial parks, a resource recovery power plant, a baseball stadium, and schools.

During the planning of an urban reuse system, a community must decide whether or not the reclaimed water system will be interruptible. Generally, unless reclaimed water is utilized as the only source of fire protection in a community, an interruptible source of reclaimed water is acceptable. The City of St. Petersburg, Florida, for example, decided that an interruptible source of reclaimed water would be acceptable, and that reclaimed water would be utilized only as a backup for fire protection. If a community determines that a non-interruptible source of reclaimed water is needed, then reliability must be provided to ensure a continuous flow of reclaimed water. Reliability might include more than one water reclamation plant supplying the reclaimed water system, as well as additional storage to provide for fire protection needs in the case of a plant upset.

Retrofitting a developed urban area with a reclaimed water distribution system can be expensive; in some cases, however, the benefits of conserving potable water may justify the cost. For example, the water reuse system may be cost-effective if it eliminates or forestalls the need to obtain additional water supplies from considerable distances or to treat a raw water supply source of poor quality.

In newly developing urban areas, substantial cost savings may be realized by installing a dual distribution system as an integral part of the utility infrastructure as the area develops and by stipulating connection to the system as a requirement of the community's land development code. For example, in 1984 the City of Altamonte Springs enacted as part of its land development code the requirement for developers to install reclaimed water lines so that all properties within the development are provided service. The section of the code further states that: "The intent of the reclaimed water system is not to duplicate the potable water system, but rather to complement each other and thereby provide the opportunity to reduce line sizes and looping requirements of the potable water system" (Howard, Needles, Tammen, and Bergendoff, 1986a).

The Irvine Ranch Water District in California studied the economic feasibility of expanding its urban dual distribution system to provide reclaimed water to high-rise buildings for toilet and urinal flushing. The study concluded that use of reclaimed water was feasible for flushing toilets and urinals and priming floor drain traps for buildings of six stories and higher (Young and Holliman, 1990). Following this study, an ordinance was enacted requiring all new buildings over 55 ft (17 m) high to install a dual distribution system for flushing in areas where reclaimed water is available (Irvine Ranch Water District, 1990).

3.2.1 Reclaimed Water Demand

The daily irrigation demand for reclaimed water generated by a particular urban system can be estimated from an inventory of the total irrigable acreage to be served by the reclaimed water system and the estimated weekly irrigation rates, determined by such factors as local soil characteristics, climatic conditions, and type of landscaping. In some states, recommended weekly irrigation rates may be available from water management agencies, county or state agricultural agents, and irrigation specialists. Reclaimed water demand estimates must also take into account any other permitted uses for reclaimed water within the system.

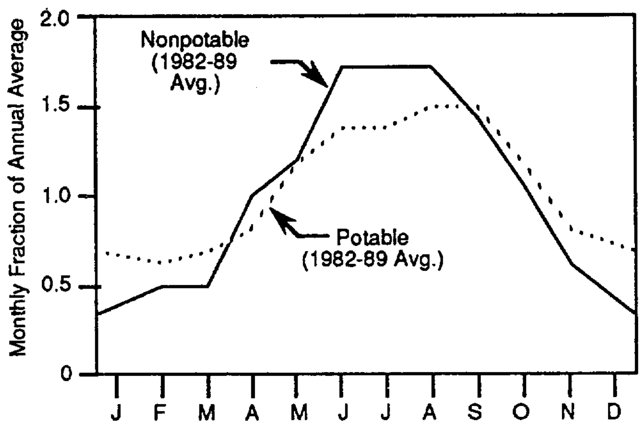
An estimation of the daily irrigation demand of reclaimed water can also be made by evaluating local water billing records. For example, in many locations, second water meters measure the volume of potable water used outside the home, primarily for irrigation. An evaluation of the water billing records in Manatee County, Florida, has shown that the average irrigation demand measured on the residential second meters is approximately 660 gpd (2.5 m^3/d), compared to 185 gpd (0.7 m^3/d) on the first meter, which measures the amount of water for in-house uses (CDM, 1990b). Using these data to estimate the daily demand for reclaimed water for residential use indicates that a 78-percent reduction in residential potable water demand could be accomplished in residential areas served by a dual distribution system for residential irrigation in Manatee County.

Water use records can also be used to estimate the seasonal variation in reclaimed water demand. Figure 23 shows the historic monthly variation in the potable and reclaimed water demand for the Irvine Ranch Water District, while Figure 24 shows the historic monthly variation in the potable and nonpotable water demand for St. Petersburg, Florida. Although the seasonal variation in demand is different between the two communities, both show a similar trend in the seasonal variation between the potable and nonpotable demand. Figures 23 and 24 illustrate how fluctuations in potable water demand may be influenced by nonpotable uses such as irrigation, even where a significant portion of the potable demand is met by an alternate source of water.

For potential reclaimed water users such as golf courses that draw their irrigation water from onsite wells, an evaluation of the permitted withdrawal rates can be used to estimate the reclaimed water demand.

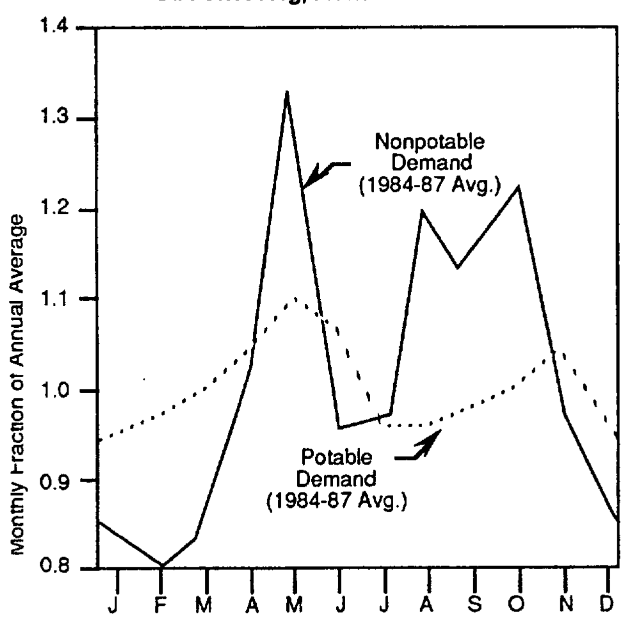
In assessing the reuse demand for an urban reuse system, demands for uses other than irrigation must also be determined. Demands for industrial users, as well as commercial users such as car washes, can be estimated from water use or billing records. Demands for recreational impoundments can be estimated by determining the volume of water required to maintain a desired water elevation in the impoundment.

Figure 23. Potable and Nonpotable Water Use Monthly Historic Demand Variation Irvine Ranch Water District



Source: Irvine Ranch Water District, 1991.

Figure 24. Potable and Nonpotable Water Use Monthly Historic Demand Variation, St. Petersburg, Florida



Source: Camp Dresser & McKee Inc., 1990b.

For those systems using reclaimed water for toilet flushing as part of their urban reuse system, water use records can again be used to estimate this demand. According to Grisham and Fleming (1989) toilet flushing can account for up to 45 percent of the indoor residential water demand. A study conducted by the Irvine Ranch Water District in 1987 on commercial high-rise water usage showed that 70 to 85 percent of the water used in an office high-rise is used for toilet and urinal flushing (Young and Holliman, 1990).

3.2.2 Reliability and Public Health Protection

In the design of an urban reclaimed water distribution system, the most important considerations are the reliability of service and protection of public health. Treatment to meet appropriate water quality and quantity requirements and system reliability are addressed in Section 2.4. The following safeguards must be considered during the design of any dual distribution system:

- Assurance that the reclaimed water delivered to the customer meets the water quality requirements for the intended uses,
- Prevention of improper operation of the system,
- Prevention of cross connections with potable water lines, and
- Prevention of improper use of nonpotable water.

To avoid cross connections, all equipment associated with reclaimed water systems must be clearly marked. National color standards have not been established, but accepted practice by manufacturers and many cities is purple. A more detailed discussion of distribution safeguards and cross connection control measures is presented in Section 2.6.1, Conveyance and Distribution Facilities.

3.2.3 Design Considerations

Urban water reuse systems have two major components:

- Water reclamation facilities for reclaimed water production;
- Reclaimed water distribution system, including operational storage and high-service pumping facilities.

3.2.3.1 Water Reclamation Facilities

Water reclamation facilities must provide the required treatment to meet appropriate water quality standards for the intended use. In addition to secondary treatment, filtration and disinfection are generally required for reuse in an urban setting. Because urban reuse usually involves irrigation of properties with unrestricted public access or other types of reuse where human exposure to the reclaimed water is likely, reclaimed water must be of a higher quality than may be necessary for other reuse applications. On the other hand, where a large customer needs a higher quality reclaimed water than afforded by this treatment, the customer may have to provide the additional treatment onsite, as is commonly done with potable water. Treatment requirements are presented in Section 2.4. Figure 25 is a flow diagram for a typical water reclamation plant in the reuse system of the Sanitation Districts of Los Angeles County. Secondary treatment, filtration, and disinfection are provided, and the sludge is returned to the trunk sewer for processing at a central wastewater treatment plant.

3.2.3.2 Distribution System

Operational storage facilities and high-service pumping are usually located at the water reclamation facility. However in some cases, particularly for large cities, operational storage facilities may be located at appropriate locations on the system and/or near the reuse sites, and the latter may be provided by the utility or the customer. When located near the pumping facilities, ground or elevated tanks may be used; when located within the system, operational storage is generally elevated.

Sufficient storage to accommodate diurnal flow variation is essential in the operation of a reclaimed water system. The volume of storage required can be determined from the daily reclaimed water demand and supply curves. Reclaimed water is normally produced 24 hours/d in accordance with the diurnal flow at the water reclamation plant and may flow to ground storage to be pumped into the system or into a clear well for high-lift pumping to elevated storage facilities. Covered storage is preferred to preclude biological growth and maintain a chlorine residual. Refer to Section 2.6.2 for a discussion of operational storage.

Since variations in the demand of reclaimed water also occur seasonally, large volumes of seasonal storage may also be necessary if all available reclaimed water is to be used, although this may not be economically practical. The selected location of the seasonal storage facility will also have an effect on the design of the distribution system. A detailed discussion of seasonal storage requirements is given in Section 2.5.

The design of an urban distribution system is similar in many respects to that of the municipality's potable water distribution system, and the use of materials of equal quality for construction is recommended. System integrity should be assured; however, the reliability of the system need not be as stringent as potable water system unless reclaimed water is being used as the only source of fire protection. No special measures are required to pump, deliver, and use the water. Also, no modifications other than identification of equipment or materials are required because reclaimed water is being used. However for service lines in urban settings, different materials may be desirable for more certain identification.

The design of distribution facilities is based on topographical conditions as well as reclaimed water demand requirements. If topography has wide variations, multi-level systems may have to be used. Distribution mains must be sized to provide the peak hourly demands at a pressure adequate for the user being served. Pressure requirements for a dual distribution system vary depending on the type of user being served. Pressures for irrigation systems can be as low as 10 psi (70 kPa) if additional booster pumps are provided at the point of delivery, and maximum pressures can be as high as 100 to 150 psi (700 to 1,000 kPa).

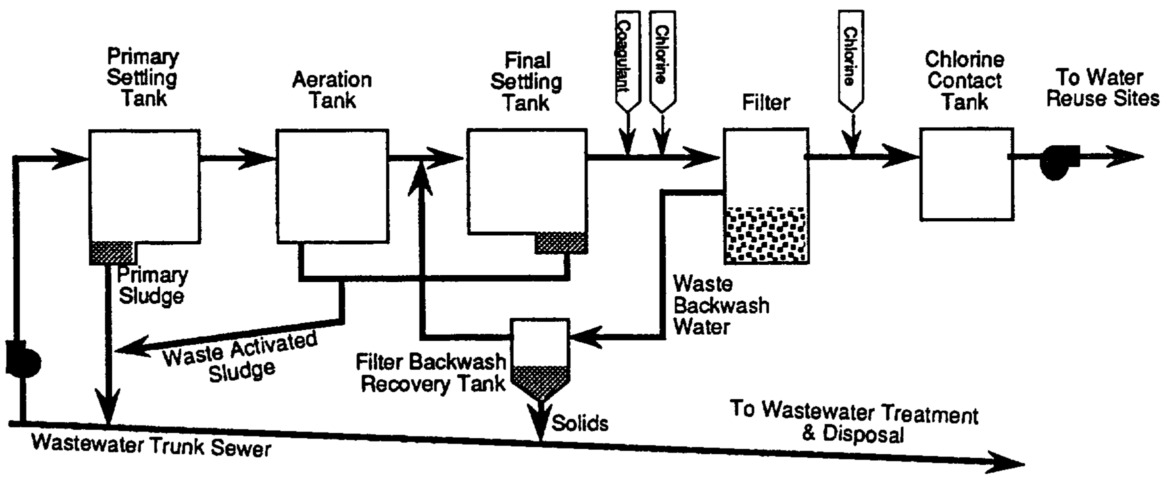
The peak hourly distribution mains rate of use, which is a critical consideration in sizing the delivery pumps and distribution mains, may best be determined by observing and studying local urban practices and considering time of day and rates of use by large users to be served by the system. The following design peak factors have been used in designing urban reuse systems:

System	Peaking Factor
Altamonte Springs, Florida (HNTB, 1986a)	2.90
Apopka, Florida (Godlewski, *et al.*, 1990)	4.00
Aurora, Colorado (Johns *et al.*, 1987)	2.50
Boca Raton, Florida (CDM, 1990a)	2.00
Irvine Ranch Water District (IRWD, 1991)	
- Landscape Irrigation	6.80
- Golf Course and Agricultural Irrigation	2.00
Sea Pines, S. C. (Hirsekorn and Ellison, 1987)	2.00
St. Petersburg, Florida (CDM, 1987)	2.25

For reclaimed water systems that include fire protection as part of their service, fire flow plus the maximum daily demand should be considered when sizing the distribution system. This scenario is not as critical in sizing the delivery pumps since it will likely result in less pumping capacity, but is critical in sizing the distribution mains because fire flow could be required at any point in the system, resulting in high localized flows.

The Irvine Ranch Water District Water Resources Master Plan recommends a peak hourly use factor of 6.8 when reclaimed water is used for landscape irrigation and a peak factor of 2.0 for agricultural and golf course irrigation

Figure 25. Typical Water Reclamation Plant Process for Urban Reuse



systems (IRWD, 1991). The peak factor for landscape irrigation is higher because reclaimed water use is restricted to between 9 p.m. and 6 a.m. This restriction does not apply to agricultural or golf course use.

Generally, there will be "high-pressure" and "low-pressure" users on an urban reuse system. The high-pressure users receive water directly from the system at pressures suitable for the particular type of reuse. Examples include residential and landscape irrigation, industrial process and cooling water, car washes, fire protection, and toilet flushing in commercial and industrial buildings. The low-pressure users receive reclaimed water into an onsite storage pond to be repumped into their reuse system. Typical low-pressure users are golf courses, parks, and condominium developments which utilize reclaimed water for irrigation. Other low pressure uses include delivery of reclaimed water to landscape or recreational impoundments.

Typically, urban dual distribution systems operate at a minimum pressure of 50 psi (350 kPa), which will satisfy the pressure requirements for irrigation of larger landscaped areas such as multi-family complexes and offices, commercial and industrial parks. Based on requirements of typical residential irrigation equipment, a minimum delivery pressure of 30 psi (210 kPa) is used for the satisfactory operation of in-ground residential irrigation systems. A minimum pressure of 50 psi (350 kPa) should also satisfy the requirements of car washes, toilet flushing, construction dust control, and some industrial users.

For users who operate at higher pressures than other users on the system, additional onsite pumping will be required to satisfy the pressure requirements. For example, golf course irrigation systems typically operate at higher pressures (100-200 psi [700 kPa-1,400 kPa]), and if directly connected to the reclaimed water system, will likely require a booster pump station. Repumping may be required in high-rise office buildings using reclaimed water for toilet flushing. Additionally, some industrial users may operate at higher pressures.

The design of a reuse transmission system is usually accomplished through the use of computer modeling, with portions of each of the sub-area distribution systems representing demand nodes in the model. The demand of each node is determined from the irrigable acreage tributary to the node, the irrigation rate, and the daily irrigation time period. Additional demands for uses other than irrigation, such as fire flow protection, toilet flushing, and industrial uses must also be added to the appropriate node.

The two most common methods of maintaining system pressure under widely varying flow rates are (1) constant-speed supply pumps and system elevated storage tanks, which maintain essentially consistent system pressures, or (2) constant-pressure, variable-speed, high-service supply pumps, which maintain a constant system pressure while meeting the varying demand for reclaimed water by varying the pump speed. While each of these systems has advantages and disadvantages, either system will perform well and remains a matter of local choice. The dual distribution system of the City of Altamonte Springs, Florida, operates with constant-speed supply pumps and two elevated storage tanks, and pressures range between 55 and 60 psi (380 kPa and 410 kPa). The urban system of the Marin Municipal Water District, in California, operates at a system pressure of 50 to 130 psi (350 kPa and 900 kPa), depending upon elevation and distance from the point of supply, while Apopka, Florida, operates its reuse system at a pressure of 60 psi (410 kPa).

The system should be designed with the flexibility to institute some form of usage control when necessary and provide for the potential resulting increase in the peak hourly demand. One such form of usage control would be to vary the days per week that schools, parks, golf courses and residential areas are irrigated. In addition, large users, such as golf courses, will have a major impact on the shape of the reclaimed water daily demand curve and hence on the peak hourly demand, depending upon how the water is delivered to them. The reclaimed water daily demand curve may be "flattened" and the peak hourly demand reduced if the reclaimed water is discharged to golf course ponds over a 24-hour period or during the daytime hours when demand for residential landscape irrigation is low. These methods of operation can reduce peak demands, thereby reducing storage requirements.

3.3 Industrial Reuse

Industrial reuse represents a significant potential market for reclaimed water in the U.S. and other developed countries. Although industrial uses accounted for only about 8 percent of the total U.S. water demands in 1985, in some states, industrial demands accounted for as much as 43 percent of a state's total water demands. Reclaimed water is ideal for many industries where processes do not require water of potable quality. Also, industries are often located near populated areas where centralized wastewater treatment facilities already generate an available source of reclaimed water.

Reclaimed water for industrial reuse may be derived from in-plant recycling of industrial wastewaters and/or municipal water reclamation facilities.

Recycling within an industrial plant is usually an integral part of the industrial process and must be developed on a case-by-case basis. Industries, such as steel mills, breweries, electronics, and many others, treat and recycle their own wastewater either to conserve water or to meet or avoid stringent regulatory standards for effluent discharges. This document does not discuss in-plant recycling; however, ample information and guidelines are available from industrial associations and regulatory authorities.

Industrial uses for reclaimed water include:

- Evaporative cooling water,
- Boiler-feed water
- Process water, and
- Irrigation and maintenance of plant grounds.

Of these uses, cooling water is currently the predominant industrial reuse application. In most industries, cooling creates the single largest demand for water within a plant. According to Keen and Puckorius (1988), a small petroleum refinery (40,000 barrels/d) or a 250-MW utility power plant will need about 1 to 2 mgd (44-88 L/s) of makeup water for a recirculating cooling system. Worldwide, the majority of industrial plants using reclaimed water for cooling are utility power stations.

3.3.1 Cooling Water

3.3.1.1 Once-Through Cooling Systems

Once-through cooling systems use water to cool the process equipment and then discharge the heated water after a single use. Because once-through cooling systems use such large volumes of water, reclaimed water is rarely considered a feasible source. For instance, flow for a once-through cooling system at a typical 1,000-MW fossil fuel power plant would be approximately 650 mgd (28,500 L/s), as compared to recirculating systems, such as wet towers and cooling ponds that would use approximately 9 and 6.5 mgd (395 and 285 L/s), respectively (Breitstein and Tucker, 1986).

In the largest single industrial reuse project in the U.S., the Bethlehem Steel Company in Baltimore, Maryland, uses approximately 100 mgd (4,380 L/s) of treated wastewater effluent from Baltimore's Back River WWTF for processing and cooling in a once-through system (Water Pollution Control Federation, 1989). Generally, however, once-through cooling systems require too large a volume of water to rely on public water supplies. Because water quality requirements for these cooling systems are generally not restrictive, large lakes, rivers, and even saltwater can be used, in some cases with little, if any, treatment.

3.3.1.2 Recirculating Cooling Systems

Recirculating cooling systems use water to absorb process heat, then transfer the heat from the water by evaporation, and recirculate the water for additional cooling cycles. This recirculating cooling process may employ cooling towers or cooling ponds.

a. Cooling Towers

Cooling towers are designed to take advantage of the water's high heat of evaporation, i.e., one volume of evaporated water will cause 100 volumes to drop in temperature by approximately 10°F. Dry air is brought through the sides or bottom of the tower while water is pumped to the top of the tower's packing material. The water is broken into droplets to increase air/water contact, and then brought into contact with the upcoming air, which causes a portion of the water to evaporate. The cooled water droplets collect at the bottom of the tower and then are recycled.

Evaporation and wind action at the top of the tower (drift) result in a water loss that must be replaced. To prevent an unacceptable build-up of salt contaminants due to evaporation, a portion of the recirculating water is also continuously wasted as "blowdown," and a source of make-up water is required. Makeup water must be of high quality since any contaminants in the water are concentrated many times during the cooling cycle (Asano and Mujeriego, 1988).

Cooling tower make-up water constitutes a large percentage of the total water used (from 25 to 50 percent) in such industries as electric power stations, chemical plants, metal factories, and oil refineries. The cooling tower recirculating water system is almost always a closed loop system that is operated as a separate process with its own characteristic water quality requirements. The water quality is determined by ascertaining the concentration of the potential precipitants within the make-up.

The cycles of concentration, which is defined as the ratio of a concentration of a given ion or compound in the blowdown cooling water to the concentration in the make-up water, is indicative of the number of times that the cooling water is recirculated. According to Keen and Puckorius (1988), most cooling systems are operated in the range of 5 to 10 cycles of concentration. Above this range, the small amount of water conserved is rarely justified by the increased risk of scaling and SS deposition.

Regulatory constraints on waste discharges often require treatment of the blowdown water. Treatment methods vary according to the specific discharge standards and may include temperature and pH adjustments and ion exchange for metals removal. The discharge limits and the costs of removing the contaminants can place limits on the cycles of concentration.

b. Cooling Ponds

Cooling ponds may also be used as closed recirculating cooling systems. The pond water serves as the source of cooling water, and surface evaporation from the pond is the mechanism for cooling the heat-exchanged water. The critical parameter in pond design is the surface area required for cooling the heated water. The approximation used for power plant cooling ponds is 1 to 3 ac (2.5-7.5 ha)/MW of generated electricity (Gehm, 1976). Cooling ponds are attractive because of their low capital costs, large storage capacity, and ability to function without makeup water for extended periods. However, their drawbacks include potential groundwater contamination, large land requirements, and maintenance problems involving algae and weeds.

The City of Fort Collins, Colorado, supplies reclaimed water to the Platte River Power Authority for cooling the 250-MW Rawhide energy station (Fooks *et al.*, 1987). The recirculating cooling system includes a 5.2-billion gal (20 million m^3) cooling pond to supply 170,000 gpm (10,700 L/s) to the condenser and auxiliary heat exchangers. The water reclamation facility provides complete-mix activated sludge treatment with provisions for polymer addition, followed by final clarification, chlorination, and dechlorination with sulfur dioxide. Additional treatment for phosphorus removal is provided at the energy station to deliver a maximum phosphorus concentration of 0.2 mg/L. After about 2 years of operation, the cooling lake deteriorated in aesthetic appearance and chemical quality, and a limnological management program was instituted to provide aeration and minnow control in the cooling lake.

3.3.1.3 Cooling Water Quality Requirements

The most frequent water quality problems in cooling water systems are scaling, corrosion, biological growth, fouling, and foaming. These problems arise from contaminants in potable water as well as reclaimed water, but the concentrations of some contaminants in reclaimed water may be higher. Table 13 lists water quality criteria for cooling water supplies.

In Burbank, California, about 5 mgd (219 L/s) of municipal secondary effluent has been successfully utilized for cooling water make-up in the city's power generating plant since 1967. The effluent is of such good quality that treatment consisting of additional chlorine, acid, and corrosion inhibitors makes the reclaimed water nearly equal in quality to fresh water.

The City of Las Vegas and Clark County Sanitation District used 90 mgd (3,940 L/s) of secondary effluent to supply 35 percent of the water demand in power generating stations operated by the Nevada Power

Table 13. Recommended Cooling Water Quality Criteria for Make-Up Water to Recirculating Systems

Parameter[a]	Recommended Limit[b]
Cl	500
TDS	500
Hardness	650
Alkalinity	350
pH[c]	6.9-9.0
COD	75
TSS	100
Turbidity[c]	50
BOD[c]	25
Organics[d]	1.0
NH4 - N[c]	1.0
PO_4[c]	4
SiO_2	50
Al	0.1
Fe	0.5
Mn	0.5
Ca	50
Mg	0.5
HCO3	24
SO4	200

[a]All values in mg/L except pH.
[b]Water Pollution Control Federation, 1989.
[c] From Goldstein *et al.*, 1979.
[d]Methylene blue active substances.

Company. The power company provides additional treatment consisting of two-stage lime softening, filtration, and chlorination prior to use as cooling tower make-up. A reclaimed water reservoir provides backup for the water supply.

In Odessa, Texas, three industries have used approximately 2.5 mgd (110 L/s) of municipal effluent for cooling tower make-up and boiler feed for over 20 years. Secondary effluent is treated by cold lime softening followed by filtration prior to use by the industries. This water is used directly for cooling tower make-up; water use for boiler feed is treated by two-bed demineralization before use (Water Pollution Control Federation, 1989).

a. Scaling

The cooling water must not lead to the formation of scale, i.e. hard deposits. Such deposits reduce the efficiency of the heat exchange. The principal causes of scaling are calcium (as carbonate, sulfate, and phosphate) and magnesium (as carbonate and phosphate) deposits.

Scale control for reclaimed water is achieved through chemical means and sedimentation. Acidification or addition of scale inhibitors can control scaling. Acids (sulfuric, hydrochloric, and citric acids and acid gases such as carbon dioxide and sulfur dioxide) and other chemicals (chelants such as EDTA and polymeric inorganic phosphates) are often added to increase the water solubility of scale-forming constituents, such as calcium and magnesium (Strauss and Puckorius, 1984).

Lime softening, commonly used to treat reclaimed water for cooling systems, significantly increases the cycles of concentration. The lime removes carbonate hardness and the soda ash removes the noncarbonate hardness. Other methods used to control scaling are alum treatment and sodium ion exchange, but the higher costs of these processes limit their use.

b. Corrosion

The recirculated water must not be corrosive to metal in the cooling system. High total dissolved solids (TDS) promotes corrosion by increasing the electrical conductivity of the water. The concentrations of TDS in municipally treated reclaimed water, generally two to five times higher than in potable water, can increase electrical conductivity and promote corrosion. Dissolved gases and certain metals with high oxidation states also promote corrosion.

Corrosion may also occur when acidic conditions develop in the cooling water. The Jones Station power plant in Lubbock, Texas, reported that the ammonia present in reclaimed water was converted to nitrates in the recirculating cooling water, resulting in a lowering of the pH from a range of 7.4 to 7.9 to a value of 6.5 or less. The pH was adjusted by adding carbon dioxide to increase the bicarbonate alkalinity of the cooling water (Treweek *et al.*, 1981).

Corrosion inhibitors such as chromates, polyphosphates, zinc, and polysillicates can also be used to reduce the corrosion potential of the cooling water. These substances may need to be removed from the blowdown prior to discharge. The alternative to chemical addition is ion exchange or reverse osmosis, but high costs limit their use (Strauss and Puckorius, 1984).

c. Biological Growth

Reclaimed water used in cooling systems must not supply nutrients or organics [biochemical oxygen demand (BOD)] that promote the growth of slime-forming organisms. The moist environment in the cooling tower is conducive to biological growth. Microorganisms can significantly reduce the heat transfer efficiency, reduce water flow, and in some cases generate corrosive by-products (Troscinski and Watson, 1970; California State Water Resources Control Board, 1980; Goldstein *et al.*, 1979).

The reduction of BOD and nutrients during treatment reduces the potential of the reclaimed water to sustain microorganisms. Chlorine is the most common biocide used to control biological growth because of its low cost, availability, and ease of operation. Chlorination is also used as a disinfectant to reduce potential pathogens in the reclaimed water. Frequent chlorination and shock treatment is generally adequate. Chlorine gas (purchased as liquid chlorine) is used most often, but it may also be applied as sodium hypochlorite as a liquid or solid. Chlorine dioxide is also frequently used.

At the City of Lakeland, Florida, which uses reclaimed water from a secondary treatment facility for power plant cooling, the system design of four to six cycles was reduced significantly due to biological growth and fouling of the cooling tower. Biological mass accumulated in the tower to such an extent that structural stability was threatened. The problem was solved by instituting a pretreatment program to reduce BOD, phosphorus, and SS (Libey and Webb, 1985).

On the other hand, the Orlando (Florida) Utilities Commission has reported no biological accumulation or fouling problems in the cooling system of the C.H. Stanton energy facility, which uses approximately 5 mgd (219 L/s) of highly treated reclaimed water (5 mg/L BOD, 5 mg/L TSS, 2 mg/L TN and 1 mg/L P) from an Orange County WWTF. Prior to use, the energy facility also provides pH adjustment, rechlorination, scale inhibitors, and anti-foaming agents.

In Hillsborough County, Florida, a municipal water reclamation facility provides reclaimed water for cooling a 1,200-ton/d, waste-to-energy facility and treats the blowdown water wasted from the cooling towers. The reclaimed water from the advanced treatment system meets the following water quality standards: BOD, 20 mg/L; TSS, 5 mg/L; total nitrogen, 20 mg/L; fecal coliform, <1/100 mL; and pH, 6 to 8.5. The reclaimed water is treated with additional chemicals at the waste-to-energy facility to prevent algae growth and biological buildup in the cooling system. Approximately 330,000 gpd (14 L/s) of used cooling water is discharged back to the wastewater treatment plant (Tortora and Hobel, 1990).

d. Fouling

Fouling is controlled by preventing the formation and settling of particulate matter. Chemical coagulation and filtration during the phosphorus removal treatment phase significantly reduce the contaminants that can lead to fouling. Chemical dispersants are also used as required.

3.3.2 Boiler-Feed Water

The use of reclaimed water differs little from the use of conventional public supplies for boiler-feed water; both require extensive additional treatment. Quality requirements for boiler-feed make-up water are dependent upon the pressure at which the boiler is operated as shown in Table 14. Generally the higher the pressure, the higher the quality of water required. Very high pressure boilers require makeup water of distilled quality.

In general, both potable water and reclaimed water used for boiler water makeup must be treated to reduce the hardness of the boiler-feed water to close to zero. Removal or control of insoluble salts of calcium and magnesium and control of silica and aluminum are required since these are the principal causes of scale build-up in boilers. Depending on the characteristics of the reclaimed water, lime treatment (including flocculation, sedimentation, and recarbonation) might be followed by multi-media filtration, carbon adsorption, and nitrogen removal. High purity boiler-feed water for high-pressure boilers might also require treatment by reverse osmosis or ion exchange. High alkalinity may contribute to foaming, resulting in deposits in superheater, reheater, and turbines. Bicarbonate alkalinity, under the influence of boiler heat, may lead to the release of carbon dioxide, which is a source of corrosion in steam-using equipment. The considerable treatment and the relatively small amounts of makeup required, make boiler-feed a poor candidate for reclaimed water.

3.3.3 Industrial Process Water

The suitability of reclaimed water for use in industrial processes depends upon the particular use. For example, the electronics industry requires water of almost distilled quality for washing circuit boards and other electronic components. On the other hand, the tanning industry can use relatively low-quality water. Requirements for textiles, pulp and paper, and metal fabricating are intermediate. Thus, in investigating the feasibility of industrial reuse with reclaimed water, the potential users must be contacted to determine specific requirements for process water. Table 15 presents industrial process water quality requirements for a variety of industries. Table 16 summarizes some of the water quality concerns for industrial water reuse and potential treatment processes.

3.3.3.1 Pulp and Paper

Reuse of reclaimed water in the paper and pulp industry is a function of cost and grade of paper. The higher the quality of paper, the more sensitive to water quality. Impurities found in water, particularly certain metal ions and color bodies, can cause the paper produced to change color with age.

Table 14. Recommended Industrial Boiler-Feed Water Quality Criteria

Parameter*	Low Pressure (<150 psig)	Intermediate Pressure (150-700 psig)	High Pressure (>700 psig)
Silica	30	10	0.7
Aluminum	5	0.1	0.01
Iron	1	0.3	0.05
Manganese	0.3	0.1	0.01
Calcium	**	0.4	0.01
Magnesium	**	0.25	0.01
Ammonia	0.1	0.1	0.1
Bicarbonate	170	120	48
Sulfate	**	**	**
Chloride	**	**	**
Dissolved solids	700	500	200
Copper	0.5	0.05	0.05
Zinc **	0.01	0.01	
Hardness	350	1.0	0.07
Alkalinity	350	100	40
pH, units	7.0 - 10.0	8.2 - 10.0	8.2 - 9.0
Methylene blue active substances	1	1	0.5
Carbon tetrachloride extract	1	1	0.5
Chemical oxygen demand	5	5	1.0
Hydrogen sulfide	**	**	**
Dissolved oxygen	2.5	0.007	0.0007
Temperature, °F	**	**	**
Suspended Solids	10	5	0.5

* Recommended limits in mg/L except for pH (units) and temperature (°F).

** Accepted as received (if meeting other limiting values); has never been a problem at concentrations encountered.

Source: EPA, 1980b.

Major considerations associated with the use of reclaimed water in the pulp and paper industry include (Camp Dresser & McKee, 1982):

- Biological growth may cause clogging of equipment and odors and may affect the texture and uniformity of the paper. Chlorination (3 mg/L residual) has been found adequate to control micro-organisms.
- Corrosion and scaling of equipment may result from the presence of silica, aluminum, and hardness.
- Discoloration of paper may occur due to iron, manganese, or micro-organisms. Suspended solids may decrease brightness of paper.

3.3.3.2 Chemical Industry

The water quality requirements for the chemical industry vary greatly according to production requirements. Generally, waters in the neutral pH range (6.2 to 8.3), moderately soft, with low turbidity, SS, and silica are required; dissolved solids and chloride content are not critical (Water Pollution Control Federation, 1989).

3.3.3.3 Textile Industry

Waters used in textile manufacturing must be nonstaining; hence, they must be low in turbidity, color, iron, and manganese. Hardness may cause curds to deposit on the textiles and may cause problems in some of the processes that use soap. Nitrates and nitrites may cause problems in dyeing.

3.3.3.4 Petroleum and Coal

Processes for the manufacture of petroleum and coal products can usually tolerate water of relatively low quality. Waters generally must be in the 6 to 9 pH range and have moderate SS of no greater than 10 mg/L.

3.4 Agricultural Irrigation

Agricultural irrigation represents a significant fraction of the total demand for fresh water. As discussed in Chapter 2, agricultural irrigation is estimated to represent 40 percent of the total water demand nationwide (Solley *et al.*, 1988). In western states with significant agricultural production, the percentage of fresh water used for irrigation is markedly greater. For example, Figure 26 illustrates the total daily fresh water withdrawals, public water supply, and agricultural irrigation usage for

Table 15. Industrial Process Water Quality Requirements

Parameter*	Pulp & Paper: Mechanical pulping	Pulp & Paper: Chemical, unbleached	Pulp & Paper: Pulp & Paper, bleached	Chemical	Petrochem. & coal	Textiles: Sizing suspension	Textiles: Scouring, bleach & dye	Cement
Cu					0.05	0.01		
Fe	0.3	1.0	0.1	0.1	1.0	0.3	0.1	2.5
Mn	0.1	0.5	0.05	0.1		0.05	0.01	0.5
Ca		20	20	68	75			
Mg		12	12	19	30			
Cl	1,000	200	200	500	300			250
HCO_3				128				
NO_3				5				
SO_4				100				250
SiO_2		50	50	50				35
Hardness		100	100	250	350	25	25	
Alkalinity				125				400
TDS				1,000	1,000	100	100	600
TSS		10	10	5	10	5	5	500
Color	30	30	10	20		5	5	
pH	6-10	6-10	6-10	6.2-8.3	6-9			6.5-8.5
CCE								1

*All values in mg/L except color and pH.
Source: Water Pollution Control Federation, 1989.

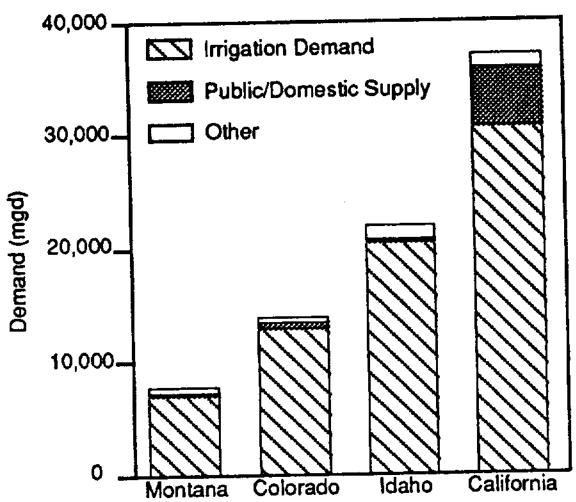
Table 16. Industrial Water Reuse Quality Concerns and Potential Treatment Processes

Parameter	Potential Problem	Advanced Treatment Process
Residual organics	Bacterial growth, slime/scale formation, foaming in boilers	Nitrification, carbon adsorption, ion exchange
Ammonia	Interferes with formation of free chlorine residual, causes stress corrosion in copper-based alloys, stimulates microbial growth	Nitrification, ion exchange, air stripping
Phosphorus	Scale formation, stimulates microbial growth	Chemical precipitation, ion exchange, biological phosphorus removal
Suspended solids	Deposition, "seed" for microbial growth	Filtration
Calcium, magnesium, iron, and silica	Scale formation	Chemical softening, precipitation, ion exchange

Source: Water Pollution Control Federation, 1989.

Montana, Colorado, Idaho, and California. These states are the top four consumers of water for agricultural irrigation, which accounts for more than 90 percent of their total water demand.

Figure 26. Comparison of Agricultural Irrigation, Public/Domestic, and Total Freshwater Withdrawals



Source: Solley *et al.*, 1988.

The total area in agricultural production in the United States and Puerto Rico is estimated to be approximately 3.6 billion ac (1.5 billion ha), of which approximately 605 million (245 million ha) are irrigated. Worldwide it is estimated that irrigation water demands exceed any other category of use by a factor of 10 (Pair *et al.*, 1983).

A significant portion of existing water reuse systems supply reclaimed water for agricultural irrigation. In Florida, agricultural irrigation accounts for approximately 34 percent of the total volume of reclaimed water used within the state (Florida Department of Environmental Regulation, 1990). In California, agricultural irrigation accounts for approximately 63 percent of the total volume of reclaimed water used within the state (California State Water Resources Control Board, 1990). Figure 27 shows the percentages of the types of crops irrigated with reclaimed water in California.

In California, Florida, and Texas, the following volumes of reclaimed water are being used for agricultural irrigation.

State	Agricultural Reuse mgd	Agricultural Reuse m^3/s
California	150	570×10^3
Florida	90	340×10^3
Texas	290*	$1,100 \times 10^{3}$*

* This is based on the design flow of the WWTP providing water and may exceed actual use.

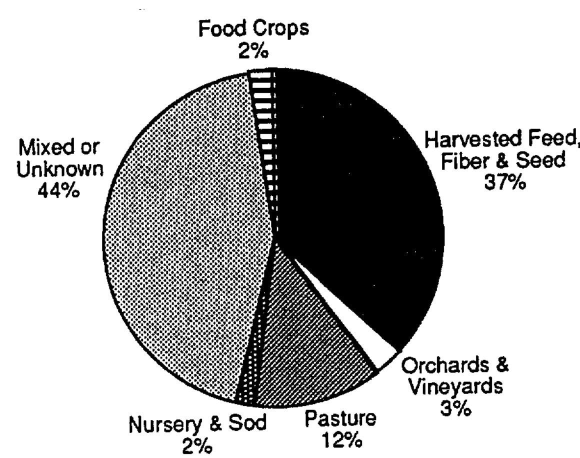
Given the high water demands for agricultural irrigation, the significant water conservation benefits of reuse in agriculture, and the opportunity to integrate agricultural reuse with other reuse applications, planning water reuse programs will often involve the investigation of agricultural irrigation.

This section discusses the considerations specific to water reuse programs for agricultural irrigation:

- ❑ Agricultural irrigation demands
- ❑ Reclaimed water quality for agricultural irrigation
- ❑ System design considerations

The technical issues common to all reuse programs are discussed in Chapter 2, and the reader is referred to the following subsections for this information: 2.4 - Treatment Requirements, 2.5 - Seasonal Storage Requirements, 2.6 - Supplemental Facilities (conveyance and distribution, operational storage, and alternative disposal).

Figure 27. Agricultural Reuse Categories by Percent in California



Source: California State Water Resources Control Board, 1990.

3.4.1 *Estimating Agricultural Irrigation Demands*

Because crop water requirements vary with climatic conditions, the need for supplemental irrigation will vary from month to month throughout the year. This seasonal variation is a function of rainfall, temperature, crop type, and stage of plant growth, and other factors depending on the method of irrigation being used.

The supplier of reclaimed water must quantify these seasonal demands, as well as any fluctuation in the reclaimed water supply, to assure that the demand for irrigation water can be met. Unfortunately, the agricultural user is often unable to provide sufficient detail on irrigation demands for design purposes. The user's seasonal or even annual water use is seldom measured and recorded, even where water has been used for irrigation for a number of years. Expert guidance, however, is usually available through state colleges and universities and the local soil conservation service office.

Nevertheless, to assess the feasibility of reuse, the reclaimed water supplier must be able to reasonably estimate irrigation demands and reclaimed water supplies. To make this assessment in the absence of actual data on an agricultural site's water use, evapotranspiration, percolation and runoff losses, and net irrigation must be estimated, often through the use of predictive equations. As discussed in Section 2.5 (Seasonal Storage), predictive equations may also be required to model periods of low demand for the purpose of sizing storage facilities.

Irrigation Requirement = Evapotranspiration - precipitation + surface runoff + percolation losses + conveyance and distribution losses

3.4.1.1 Evapotranspiration

Evapotranspiration is defined as water either evaporated from the soil surface or actively transpired from the crop. While the concept of evapotranspiration is easily described, quantifying the term mathematically is difficult. It has been suggested that the study and restudy of evapotranspiration is one of the most popular subjects in hydrology and irrigation (Jensen *et al.*, 1990).

Evaporation from the soil surface is a function of the soil moisture content at or near the surface. As the top layer of soil dries, evaporation decreases. Transpiration, the water vapor released through the plants' surface membranes, is a function of available soil moisture, season, and stage of growth. The rate of transpiration may be further impacted by soil structure and the salt concentration in the soil water. Primary factors affecting evaporation and transpiration are relative humidity, wind, and solar radiation.

In water-critical regions, the use of weather stations to generate real-time (daily) estimates of evapotranspiration is becoming more common. The state of California has developed the California Irrigation Management Information System (CIMIS), which allows growers to obtain daily reference evapotranspiration information through a computer dial-up service. Data are made available for numerous locations within the state according to regions of similar climatic conditions. State publications provide coefficients for converting these reference data for use on specific crops, location, and stages of growth, allowing users to refine irrigation scheduling and conserve water.

Numerous equations and methods have been developed to define the evapotranspiration term. A variety of methods currently used to calculate evapotranspiration are briefly described below. The reader is referred to appropriate references for specific equations and more information on applying these methods.

a. *The Penman Equation (Jones et al., 1984; Withers and Vipond, 1980; Pair et al., 1983, Jensen et al., 1990)*

The Penman equation combines an energy balance with an experimentally derived aerodynamic equation as a means of calculating potential evapotranspiration. Because there is general agreement that the Penman or a modified form of the Penman equation provides the most reliable means of estimating evapotranspiration, the Penman equation is recommended when possible. However, it is often difficult to obtain the meteorological data required to calculate this equation. For example, dew point temperatures are not available in many locations. In addition, wind speed is normally not measured at 2 m above a grassed surface at most U.S. weather stations as required for this method. Even where the required data are available, the period of record may be insufficient to generate a data base sufficient for statistical analysis.

b. *Pan Evaporation Method (Pettygrove and Asano, 1985; Jones et al., 1984; Withers and Vipond, 1980; Pair et al., 1983)*

An open pan is currently the most widely used method of estimating evapotranspiration. In addition, there are numerous locations throughout the U.S. and the world where pan evaporation data are available for a long period of record.

The concept of the pan station is straightforward. A pan of standard dimensions is filled with water and exposed to the atmosphere. The resulting water loss through evaporation can be measured and, in turn, related to the consumptive use of a crop under similar conditions. The advantages of the pan method are simplicity and low cost. However, the user must exercise caution in the use of pan data. A number of different standard pans are now in use throughout the world, each differing in construction and each with a different pan coefficient. In addition, pans are relatively sensitive to location; a pan located within a large expanse of turf will have significantly lower potential evaporation than one surrounded by bare soil.

c. Empirical Evaluations of Evapotranspiration (Jones et al., 1984; Withers and Vipond, 1980; Pair et al., 1983)

Many empirical methods have been developed to estimate evapotranspiration. The advantages of these methods are that they require only commonly measured data, such as temperature, and most are relatively simple to calculate. However, the use of a simplified equation to evaluate the complex process of evapotranspiration has inherent limitations. When selecting an appropriate empirical method, the user should identify equations developed in a similar climate. If possible, the user should re-evaluate coefficients using local data. In general, empirical equations using only temperature as a means of calculating evapotranspiration are not adequate for arid and semiarid regions (Jensen *et al.*, 1990).

The Thornthwaite and Blaney-Criddle methods of estimating evapotranspiration are two of the most cited methods in the literature. The Blaney-Criddle equation uses percent of daylight hours per month and average monthly temperature. The Thornthwaite method relies on mean monthly temperature and daytime hours. In addition to specific empirical equations, it is quite common to encounter modifications to empirical equations for use under specific regional conditions. In selecting an empirical method of estimating evapotranspiration, the potential user is encouraged to solicit input from local agencies familiar with this subject.

3.4.1.2 Effective Precipitation, Percolation and Surface Water Runoff Losses

Traditionally, the design of land application systems has attempted to account for the movement of water into and out of the application site. This approach is oriented to maximizing hydraulic capacity and, in turn, minimizing the land required for a given disposal capacity. It is quite common to find crop selection for land application sites based on the crop's ability to tolerate extended periods of excessive soil moisture. Under disposal-oriented design, as specified in most state regulations, the application of effluent in a manner resulting in surface runoff is discouraged or prohibited. However, the designer typically provides for runoff of rainfall. In many cases, runoff losses are assumed to be a fixed percentage of total rainfall throughout the year based on Soil Conservation Service (SCS) runoff coefficients for a specific soil type and ground cover.

Percolation losses are generally based on site-specific investigation of the hydrogeologic conditions of the selected land application site. The EPA manual *Land Treatment of Municipal Wastewater* (EPA, 1981) recommends that the system percolation losses be estimated between 4 to 10 percent of the minimum soil permeability encountered on the site.

The allowable percolation loss from a land application site is not specifically regulated, but may be indirectly controlled by groundwater quality regulations. While the parameters related to maintenance of groundwater quality may vary from state to state, most areas specifically require nitrate levels of less than 10 mg/L, mainly to minimize the possibility of methemoglobinemia or "blue baby syndrome," which could result from consumption of groundwater containing elevated levels of nitrate. This water quality requirement is applicable to almost all land application systems using municipal wastewater effluents due to the nitrogen content of the reclaimed water.

The approach for the beneficial reuse of reclaimed water will, in most cases, vary significantly from land treatment. Specifically, the reclaimed water is treated as a resource to be used judiciously. The prudent allocation of this resource becomes even more critical in locations where reclaimed water is assigned a dollar value, thereby becoming a commodity. Where there is a cost associated with using reclaimed water, the recipient of reclaimed water would seek to balance the cost of supplemental irrigation against the expected increase in crop yields to derive the maximum economic benefit. Thus, percolation losses will be minimized because they represent the loss of water available to the crop and wash fertilizers out of the root zone. An exception to this occurs when the reclaimed water has a high salt concentration, and excess application is required to prevent the accumulation of salts in the root zone (see Section 3.4.2).

In evaluating the need for supplemental irrigation, it is desirable to estimate that fraction of the precipitation which actually becomes available to the crop, called "effective rainfall." The amount of effective rainfall will be influenced by rainfall intensity, soil infiltration rates, soil water storage capacity, management of irrigation water, and rooting depth of the crop. As with methods of estimating evapotranspiration, a precise calculation of effective rainfall is not possible. The SCS has developed an empirical method (USDA, 1967) that provides a reasonable estimate of effective rainfall; however, site-specific information should be used if available.

Irrigation demand is that water required to meet the needs of the crop and overcome system losses. System losses will consist of percolation, surface water runoff, as well as transmission and distribution losses. In addition to the above losses, the application of water to crops will include evaporative losses or losses due to wind drift. These losses may be difficult to quantify individually and are often estimated in a single system efficiency. The actual efficiency of a given system will be site specific and will vary widely depending on management practices followed. Irrigation efficiencies typically range from 35 to 90 percent (Pettygrove and Asano, 1985). A general range by type of irrigation system is as follows:

- Surface (flood) irrigation - 50 - 70 percent
- Sprinkler irrigation - 65 - 70 percent
- Drip/trickle irrigation - 85 - 90 percent

Combining the various losses, the net irrigation may also be written as:

Total Irrigation Demand = (ET - effective rainfall)/ system application efficiency

When using closed pipes to transmit reclaimed water, water system losses will be similar to those observed in potable distribution systems and, in most cases, should not represent a significant portion of the net demand. System losses may become significant when unlined, open channels are used to transmit water.

Since there are no hard and fast rules for selecting the most appropriate methods for projecting irrigation demands and establishing parameters for system reliability, it may be prudent to undertake several of the techniques and to verify calculated values with available records. In the interest of developing the most useful models, local irrigation specialists should be consulted.

3.4.2 Reclaimed Water Quality

General treatment requirements to ensure a reliable reclaimed water suitable for the various reuse applications are presented in Section 2.4. There are also some constituents in reclaimed water that have special significance in agricultural irrigation.

The constituents in reclaimed water of concern for agricultural irrigation are salinity, sodium, trace elements, excessive chlorine residual, and nutrients. Sensitivity is generally a function of a given plant's tolerance to these constituents encountered in the root zone or deposited on the foliage. Reclaimed water tends to have higher concentration of these constituents than the groundwater or surface water sources from which the water supply is drawn.

The types and concentrations of constituents in reclaimed wastewater depend upon the municipal water supply, the influent waste streams (i.e., domestic and industrial contributions), amount and composition of infiltration in the wastewater collection system, the wastewater treatment processes, and the type of storage facilities. In most cases, the reclaimed water is of acceptable quality if the municipal potable source is acceptable. Conditions which can have an adverse impact on reclaimed water quality may include:

- Elevated TDS levels.
- Industrial discharges of potentially toxic compounds into the municipal sewer system.
- Saltwater (chlorides) infiltration into the sewer system in coastal areas.

3.4.2.1 Salinity

Salinity is the single most important parameter in determining the suitability of a water for irrigation (Pettygrove and Asano, 1985). The tolerance of plants to salinity varies widely. Crops must be chosen carefully to ensure that they can tolerate the salinity of the irrigation water, and even then the soil must be properly drained and adequately leached to prevent salt buildup.

Leaching is the deliberate over-application of irrigation water in excess of crop needs to establish a downward movement of water and salt away from the root zone.

The formula for leaching requirement is:

(U.S. Bureau of Reclamation, 1984)

$$LR = ECiw/ECdw \times 100$$

where: ECiw = electrical conductivity of irrigation water

ECdw = electrical conductivity of drainage water and is determined by the salt tolerance of the crop to be grown

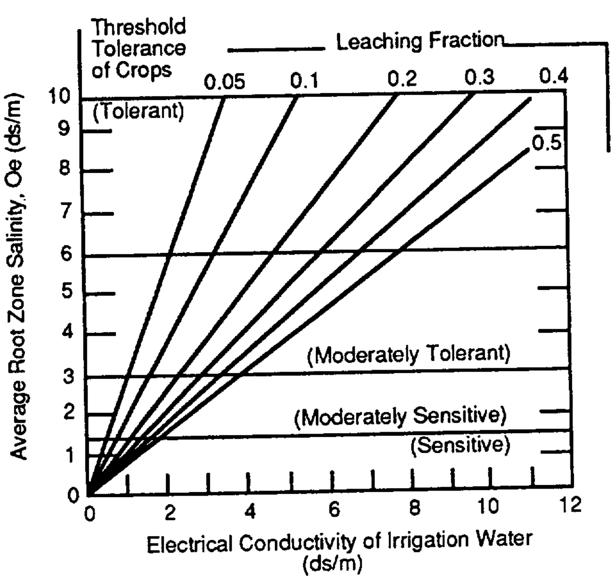
The extent of salt accumulation in the soil depends on the concentration of salts in the irrigation water and the rate at which it is removed by leaching. Salt accumulation can be especially detrimental during germination and when plants are young (seedlings), even at relatively low concentrations. Salinity is usually determined by measuring the electrical conductivity of the water, yet salinity may also be reported as TDS. Electrical conductivity of a water is a quick measure of its total dissolved salt concentration and is commonly expressed as ds/m or mmho/cm (Pettygrove and Asano, 1985). The TDS is commonly expressed as mg/L, a ratio of the weight of dissolved solids contained in one liter of solution.

The values for electrical conductivity (EC) and TDS are interchangeable within an accuracy of about +10 percent (Pettygrove and Asano, 1985). The equations used to convert EC to TDS is:

TDS (mg/L) x 0.00156 = EC (mmho/cm)

The EC is used as an expression of salinity in the irrigation water (ECiw), salinity in the saturated extract (ECe), and salinity in the soil solution (ECss). To determine the ECe, demineralized water is added to soil until the solid paste glistens and flows slightly. The soil paste is then filtered under suction and the solution is obtained and analyzed for electrical conductivity (Tanji, 1990). Crops are divided into the four major groups, shown in Figure 28, based on tolerance to irrigation salinity, leaching fraction, and the respective root zone salinity (ECe). Note that the leaching fraction is determined by measuring water infiltration and estimating evapotranspiration.

Figure 28. Assessing Crop Sensitivity to Salinity for Conventional Irrigation



Source: Tanji, 1990.

The following is a description of the irrigation water quality as it relates to salinity for each of the crop groups:

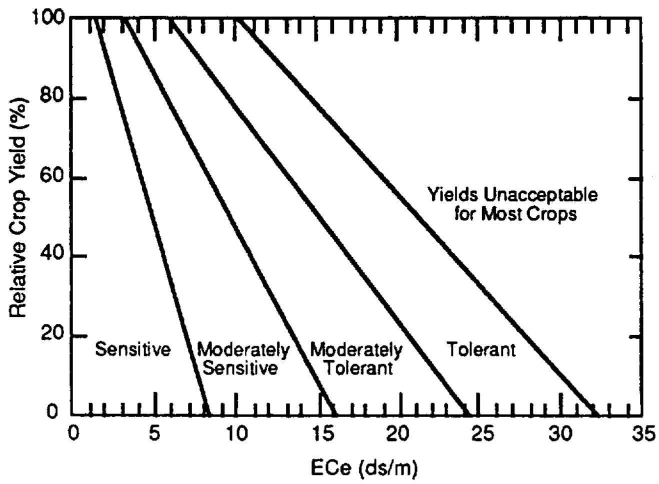
- Sensitive Crops - The water can be used for irrigation of most crops on most soils with little likelihood that soil salinity will develop. Some leaching is required, but this occurs under normal irrigation practices, except in soils of extremely low permeability.
- Moderately Sensitive Crops - The water can be used if a moderate amount of leaching occurs. Plants with moderate salt tolerance can be grown in most cases without special practices for salinity control.
- Moderately Tolerant Crops - The water cannot be used on soils with restricted drainage. Even with adequate drainage, special management for salinity control may be required, and plants with good salt tolerance should be selected.
- Tolerant Crops - The water is not suitable for irrigation under ordinary conditions, but may be used occasionally under very special circumstances. The soils must be permeable, draining must be adequate, irrigation water must be applied in excess to provide considerable leaching, and very salt-tolerant crops should be selected (Pair *et al.*, 1983).

Figure 29 shows the various crop divisions with a relationship of percent crop yield to the salinity of saturated soil extract taken from the root zone (ECe). Table 17 divides the types of crops into their respective groups based on salt tolerance at the root zone (ECe). In addition, a study in St. Petersburg, Florida, found that of the 205 species of landscape plants reviewed in a homeowner study, 55 were highly tolerant to reclaimed water, 108 were tolerant, 39 were found to need extra maintenance with reclaimed water, and only three species were not recommended (Parnell, 1987).

The concerns with salinity are its influence on: (1) the soil's osmotic potential, (2) specific ion toxicity, and (3) degradation of soil physical conditions that may occur. These conditions may result in reduced plant growth rates, reduced yields, and, in severe cases, total crop failure.

Salinity reduces the water uptake of plants by lowering the osmotic potential of the soil. This, in turn, causes the plant to use a large portion of its available energy on adjusting the salt concentration within its tissue to obtain adequate water, resulting in less energy available for plant growth. The problem is greater under hot and dry climatic conditions, because of greater plant water usage, and is even more severe when irrigation is inadequate.

Figure 29. Divisions for Classifying Crop Tolerance of Salinity



Source: Tanji, 1990.

The concentration of specific ions may cause one or more of these trace elements to accumulate in the soil and plant, and long-term buildup may result in animal and human health hazards or phytotoxicity in plants. When irrigating with municipal reclaimed water, the ions of most concern are sodium, chloride, and boron. Household detergents are usually the source of boron, and water softeners contribute sodium and chloride. Plants vary greatly in their sensitivity to specific ion toxicity. Toxicity is particularly detrimental when crops are irrigated with overhead sprinklers during periods of high temperature and low humidity. Highly saline water applied to the leaves results in direct absorption of sodium and/or chloride and can cause leaf injury.

3.4.2.2 Sodium

The potential influence sodium may have on soil properties is indicated by the sodium-adsorption-ratio (SAR), which is based on the effect of exchangeable sodium on the physical condition of the soil. The concentration of sodium in water relative to calcium and magnesium is expressed as SAR and is calculated as follows:

$$SAR = \frac{Na}{\sqrt{[(Ca + Mg)/2]}}$$

where ion concentrations, Na, Ca and Mg are expressed in meq/L

For reclaimed water, it is recommended that the SAR be adjusted for alkalinity to include a more correct estimate of calcium in the soil water following irrigation, specifically adj R_{Na}. The adjusted value is calculated as:

$$\text{adj } R_{Na} = \frac{Na}{\sqrt{(Ca_x + Mg)/2}}$$

where the Ca_X value can be determined from Table 18.

Note that the calculated (adj R_{Na}) is to be substituted for the SAR value (Pettygrove and Asano, 1985).

Sodium salts influence the exchangeable cation composition of the soil, which lowers the permeability and affects the tilth of the soil. This usually occurs within the first few inches of the soil and is related to high sodium or very low calcium content in the soil or irrigation water. Studies have also shown that in soils groups with a very high amount of organic matter or oxides show little loss of hydraulic conductivity when saturated with Na and equilibrated to very low levels of salinity (Tanji, 1990). Sodium hazard does not impair the uptake of water by plants but does impair the infiltration of water into the soil. The growth of plants is thus affected by an unavailability of soil water (Tanji, 1990). Calcium and magnesium act as stabilizing ions in contrast to the destabilizing ion (Na) in regard to the soil structure. They offset the phenomena related to the distance of charge neutralization for soil particles caused by excess sodium. Sometimes the irrigation water may dissolve sufficient calcium from calcareous soils to decrease the sodium hazard appreciably. Leaching and dissolving the calcium from the soil is of little concern when irrigating with reclaimed water because it is usually high enough in salt and calcium. Reclaimed water, however, may be high in sodium relative to calcium and may cause soil permeability problems if not properly managed.

3.4.2.3 Trace Elements

Trace elements in reclaimed water normally occur in concentrations less than a few mg/L, with usual concentrations less than 100 µg/L (Pettygrove and Asano, 1985). Some are essential for plants and animals but all can become toxic at elevated concentrations or doses (Tanji, 1990).

A study in California (Engineering Science, 1987) was performed to determine if a higher concentration of heavy

Table 17. Crop Salt Tolerance

Sensitive	Moderately Sensitive	Moderately Tolerant	Tolerant
Bean	Broad Bean	Cowpea	Barley
Paddy Rice	Corn	Kenaf	Cotton
Sesame	Flax	Oats	Guar
Carrot	Millet	Safflower	Rye
Okra	Peanut	Sorghum	Sugar Beet
Onion	Sugarcane	Soybean	Triticale
Parsnip	Sunflower	Wheat	Semi-dwarf Wheat
Pea	Alfalfa	Barley (forage)	Durum Wheat
Strawberry	Bentgrass	Grass Canary	Alkali Grass
Almond	Angleton Bluestem	Hubam Clover	Nuttail Alkali
Apple	Smooth Brome	Sweet Clover	Bermuda Grass
Apricot	Buffelgrass	Tall Fescue	Kallar Grass
Avocado	Burnet	Meadow Fescue	Desert Salt Grass
Blackberry	Alsike Clover	Harding Grass	Wheat Grass
Boysenberry	Ladino Clover	Blue Panic Grass	Fairway Wheat
Cherimoya	Red Clover	Rape	Crested Wheat
Sweet Cherry	Strawberry Clover	Rescue Grass	Tall Wheat Grass
Sand Cherry	White Dutch Clover	Rhodes Grass	Altai Wild Rye
Currant	Corn (forage)	Italian Ryegrass	Russian Wild Rye
Gooseberry	Cowpea (forage)	Perennial Ryegrass	Asparagus
Grapefruit	Grass dallis	Sundan Grass	Guayule
Lemon	Meadow Foxtail	Narrowleaf Trefoil	Jojoba
Lime	Blue Grama	Broadleaf Trefoil	
Loquat	Love Grass	Wheat (forage)	
Mango	Cicer Milkvetch	Durum Wheat (forage)	
Orange	Tall Oat Grass	Standard Crested Wheat Grass	
Passion Fruit	Oats (forage)	Intermediate Wheat Grass	
Peach	Orchard Grass	Slender Wheat Grass	
Pear	Rye (forage)	Beardless Wild Rye	
Persimmon	Sesbania	Canadian Wild Rye	
Plum; Prune	Sirato	Artichoke	
Pummelo	Sphaerophysa	Red Beet	
Raspberry	Timothy	Zucchini Squash	
Rose Apple	Big Trefoil	Fig	
White Sapote	Common Vetch	Jujube	
Tangerine	Broccoli	Papaya	
	Brussel Sprouts	Pomegranate	
	Cabbage		
	Cauliflower		
	Celery		
	Sweet Corn		
	Cucumber		
	Eggplant		
	Kale		
	Kohlrabi		
	Lettuce		
	Muskmelon		
	Pepper		
	Potato		
	Pumpkin		
	Radish		
	Spinach		
	Scallop Squash		
	Sweet Potato		
	Tomato		
	Turnip		
	Watermelon		
	Castorbean		
	Grape		

Source: Tanji, 1990.

Table 18. Salinity of Applied Water (EC_w)

(mmho/cm or dS/m)

Ratio of HCO_3/Ca	0.1	0.2	0.3	0.5	0.7	1.0	2.0	3.0	4.0	5.0	6.0	8.0
0.05	13.20	13.61	13.92	14.40	14.79	15.26	15.91	16.43	17.28	17.97	19.07	19.94
0.10	8.31	8.57	8.77	9.07	9.31	9.62	10.02	10.35	10.89	11.32	12.01	12.56
0.15	6.34	6.54	6.69	6.92	7.11	7.34	7.65	7.90	8.31	8.64	9.17	9.58
0.20	5.24	5.40	5.52	5.71	5.87	6.06	6.31	6.52	6.86	7.13	7.57	7.91
0.25	4.51	4.65	4.76	4.92	5.06	5.22	5.44	5.62	5.91	6.15	6.52	6.82
0.30	4.00	4.12	4.21	4.36	4.48	4.62	4.82	4.98	5.24	5.44	5.77	6.04
0.35	3.61	3.72	3080	3.94	4.04	4.17	4.35	4.49	4.72	4.91	5.21	5.45
0.40	3.30	3.40	3.48	3.60	3.70	3.82	3.98	4.11	4.32	4.49	4.77	4.98
0.45	3.05	3.14	3.22	3.33	3.42	3.53	3.68	3.80	4.00	4.15	4.41	4.61
0.50	2.84	2.93	3.00	3.10	3.19	3.29	3.43	3.54	3.72	3.87	4.11	4.30
0.75	2.17	2.24	2.29	2.37	2.43	2.51	2.62	2.70	2.84	2.95	3.14	3.28
1.0	1.79	1.85	1.89	1.96	2.01	2.09	2.16	2.23	2.35	2.44	2.59	2.71
1.25	1.54	1.59	1.63	1.68	1.73	1.78	1.86	1.92	2.02	2.10	2.23	2.33
1.50	1.37	1.41	1.44	1.49	1.53	1.58	1.65	1.70	1.79	1.86	1.97	2.07
1.75	1.23	1.27	1.30	1.35	1.38	1.43	1.49	1.54	1.62	1.68	1.78	1.86
2.00	1.13	1.16	1.19	1.23	1.26	1.31	1.36	1.40	1.48	1.54	1.63	1.70
2.25	1.04	1.08	1.10	1.14	1.17	1.21	1.26	1.30	1.37	1.42	1.51	1.58
2.50	0.97	1.00	1.02	1.06	1.09	1.12	1.17	1.21	1.27	1.32	1.40	1.47
3.00	0.85	0.89	0.91	0.94	0.96	1.00	1.04	1.07	1.13	1.17	1.24	1.30
3.50	0.78	0.80	0.82	0.85	0.87	0.90	0.94	0.97	1.02	1.06	1.12	1.17
4.00	0.71	0.73	0.75	0.78	0.80	0.82	0.86	0.88	0.93	0.97	1.03	1.07
4.50	0.66	0.68	0.69	0.72	0.74	0.76	0.79	0.82	0.86	0.90	0.95	0.99
5.00	0.61	0.63	0.65	0.67	0.69	0.71	0.74	0.76	0.80	0.83	0.88	0.93
7.00	0.49	0.50	0.52	0.53	0.55	0.57	0.59	0.61	0.64	0.67	0.71	0.74
10.00	0.39	0.40	0.41	0.42	0.43	0.45	0.47	0.48	0.51	0.53	0.56	0.58
20.00	0.24	0.25	0.26	0.26	0.27	0.28	0.29	0.30	0.32	0.33	0.35	0.37

Source: Adapted from Suarez, 1981.

metals could be found in plots irrigated with reclaimed water vs. well water. After a 5-year period, it was determined that there were no increasing trends with the exception of copper, which rose for all water types, yet still well below the average of California soils. It was determined that concentrations were so low (below detection for the most part), that irrigation for much longer periods would lead to the same conclusion as the 5-year test with the exception of iron and zinc (two essential plant and animal micronutrients). It was found that iron was more concentrated in plots irrigated with well water and zinc was greater with the reclaimed water. However, at the levels found for either, the uptake by plants would be greater than the accumulation from irrigation input.

In addition, it was found that the input of heavy metals from commercial chemical fertilizer impurities was far greater than that contributed by the reclaimed water.

The elements of greatest concern at elevated levels are cadmium, copper, molybdenum, nickel, and zinc. Nickel and zinc are of a lesser concern than cadmium, copper and molybdenum because they have visible adverse effects in plants at lower concentrations than the levels harmful to animals and humans. Zinc and nickel toxicity reduces as pH increases. Cadmium, copper, and molybdenum, however, can be harmful to animals at concentrations too low to affect plants.

Copper is not toxic to monogastric animals, but may be toxic to ruminants. However, their tolerance increases as available molybdenum increases. Molybdenum can also be toxic when available in the absence of copper. Cadmium is of particular concern as it can accumulate in the food chain. It does not adversely affect ruminants in the small amounts they ingest. Most milk and beef products are also unaffected by livestock ingestion of cadmium because it is stored in the liver and kidneys of the animal rather than the fat or muscle tissues.

Table 19 shows EPA's recommended limits for constituents in irrigation water.

The recommended maximum concentrations for "long-term continuous use on all soils" are set conservatively, to include sandy soils that have low capacity to leach with (and so to sequester or remove) the element in question. These maxima are below the concentrations that produce toxicity when the most sensitive plants are grown in nutrient solutions or sand cultures to which the pollutant has been added. This does not mean that if the suggested limit is exceeded that phytotoxicity will occur. Most of the elements are readily fixed or tied up in soil and accumulate with time. Repeated applications in excess of suggested levels might induce phytotoxicity. The criteria for short-term use (up to 20 years) are recommended for fine-textured neutral and alkaline soils with high capacities to remove the different pollutant elements (EPA, 1980b).

3.4.2.4 Chlorine Residual

Free chlorine residual at concentrations less than 1 mg/L usually poses no problem to plants. However, some sensitive crops may be damaged at levels as low as 0.05 mg/L. Some woody crops, however, may accumulate chlorine in the tissue to toxic levels. Excessive chlorine has a similar leaf-burning effect as sodium and chloride when sprayed directly on foliage. Chlorine at concentrations greater than 5 mg/L causes severe damage to most plants.

3.4.2.5 Nutrients

The nutrients most important to a crop's needs are nitrogen, phosphorus, potassium, zinc, boron and sulfur. Reclaimed water usually contains enough of these nutrients to supply a large portion of a crop's needs.

The most beneficial nutrient is nitrogen. Both the concentration and form of nitrogen need to be considered in irrigation water. While excessive amounts of nitrogen stimulate vegetative growth in most crops, they may also delay maturity and reduce crop quality and quantity. In addition, excessive nitrate in forages can cause an imbalance of nitrogen, potassium, and magnesium in the grazing animals and is a concern if the forage is used as a primary feed source for livestock; however, such high concentrations are usually not expected with municipal reclaimed water.

The nitrogen in reclaimed water may not be present in concentrations great enough to produce satisfactory crop yields, and some supplemental fertilizer may be necessary. This is the case in Tallahassee, Florida, where a farmer leases city-owned land supplied with reclaimed water via a center-pivot irrigation system. Even though the irrigation rate exceeds the crops' consumptive needs, the dilute nature of the nitrogen (approximately 18 mg/L) requires supplemental fertilizers at certain times of the year (Allhands and Overman, 1989).

Soils in the western U.S. may contain enough potassium, while many sandy soils of the southern U.S. do not, yet in either case, the addition of potassium with reclaimed water has little effect on the crop. Phosphorus contained in reclaimed water is usually too low to meet a crop's needs; yet over time it can build up in the soil and reduce the need for phosphorus supplementation. Excessive phosphorus does not appear to pose any problem to crops, but can be a problem in runoff to surface waters.

Numerous site specific studies have been conducted regarding the potential water quality concerns associated with reuse irrigation. A survey of agricultural systems operating in California found no indications that crop quality or quantity had deteriorated as a result of reclaimed water irrigation. In fact, several of the farmers using reclaimed water felt that crop production had been enhanced as a result of nutrients in the water (Boyle Engineering Corporation, 1981). Studies of the Tallahassee, Florida spray irrigation system noted that after 5 years of irrigation, steady state conditions with respect to ionic species on soils exchange site had not come to a steady state, but no adverse impacts on agricultural production were expected (Payne and Overman, 1987). These and other investigations suggest that reclaimed water will be suitable for most agricultural irrigation needs.

3.4.3 Other System Considerations

In addition to irrigation supply and demand and reclaimed water quality requirements, there are other

Table 19. Recommended Limits for Constituents in Reclaimed Water for Irrigation

TRACE HEAVY METALS

Constituent	Long-Term Use (mg/L)	Short-Term Use (mg/L)	Remarks
Aluminum	5.0	20	Can cause nonproductivity in acid soils, but soils at pH 5.5 to 8.0 will precipitate the ion and eliminate toxicity.
Arsenic	0.10	2.0	Toxicity to plants varies widely, ranging from 12 mg/L for Sudan grass to less than 0.05 mg/L for rice.
Beryllium	0.10	0.5	Toxicity to plants varies widely, ranging from 5 mg/L for kale to 0.5 mg/L for bush beans.
Boron	0.75	2.0	Essential to plant growth, with optimum yields for many obtained at a few-tenths mg/L in nutrient solutions. Toxic to many sensitive plants (e.g., citrus) at 1 mg/L. Usually sufficient quantities in reclaimed water to correct soil deficiencies. Most grasses relatively tolerant at 2.0 to 10 mg/L.
Cadmium	0.01	0.05	Toxic to beans, beets, and turnips at concentrations as low as 0.1 mg/L in nutrient solution. Conservative limits recommended.
Chromium	0.1	1.0	Not generally recognized as essential growth element. Conservative limits recommended due to lack of knowledge on toxicity to plants.
Cobalt	0.05	5.0	Toxic to tomato plants at 0.1 mg/L in nutrient solution. Tends to be inactivated by neutral and alkaline soils.
Copper	0.2	5.0	Toxic to a number of plants at 0.1 to 1.0 mg/L in nutrient solution.
Fluoride	1.0	15.0	Inactivated by neutral and alkaline soils.
Iron	5.0	20.0	Not toxic to plants in aerated soils, but can contribute to soil acidification and loss of essential phosphorus and molybdendum.
Lead	5.0	10.0	Can inhibit plant cell growth at very high concentrations.
Lithium	2.5	2.5	Tolerated by most crops at up to 5 mg/L; mobile in soil. Toxic to citrus at low doses - recommended limit is 0.075 mg/L.
Manganese	0.2	10.0	Toxic to a number of crops at a few-tenths to a few mg/L in acid soils.
Molybdenum	0.01	0.05	Nontoxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high levels of available molybdenum.
Nickel	0.2	2.0	Toxic to a number of plants at 0.5 to 1.0 mg/L; reduced toxicity at neutral or alkaline pH.
Selenium	0.02	0.02	Toxic to plants at low concentrations and to livestock if forage is grown in soils with low levels of added selenium.
Tin, Tungsten, & Titanium	—	—	Effectively excluded by plants; specific tolerance levels unknown
Vanadium	0.1	1.0	Toxic to many plants at relatively low concentrations.
Zinc	2.0	10.0	Toxic to many plants at widely varying concentrations; reduced toxicity at increased pH (6 or above) and in fine-textured or organic soils.

OTHER PARAMETERS

Constituent	Recommended Limit	Remarks
pH	6.0	Most effects of pH on plant growth are indirect (e.g., pH effects on heavy metals' toxicity described above).
TDS	500-2,000 mg/L	Below 500 mg/L, no detrimental effects are usually noticed. Between 500 and 1,000 mg/L, TDS in irrigation water can affect sensitive plants. At 1,000 to 2,000 mg/L, TDS levels can affect many crops and careful management practices should be followed. Above 2,000 mg/L, water can be used regularly only for tolerant plants on permeable soils.
Free Chlorine Residual	< 1 mg/L	

Source: Adapted from EPA, 1973.

considerations specific to agricultural water reuse that must be addressed. Both the user and supplier of reclaimed water may have to consider modifications in current practice that may be required to use reclaimed water for agricultural irrigation. The extent to which current irrigation practices must be modified to make beneficial use of reclaimed water will vary on a case-by-case basis. This requires that those investigating reclaimed water programs have a working knowledge of the appropriate regulations, crop requirements, and means of application. Important considerations include:

- System reliability,
- Site use control,
- Monitoring requirements,
- Runoff controls,
- Marketing incentives, and
- Irrigation equipment.

3.4.3.1 System Reliability

Two basic issues are involved in system reliability. First, as in any reuse project, when irrigation is implemented as a means of reducing or eliminating surface water discharge, the treatment and distribution facilities must operate reliably to meet permit conditions. Second, the supply of reclaimed water to the agricultural user must be reliable in quality and quantity for successful use in a farming operation.

Reliability in quality involves providing the appropriate treatment for the intended use, with special consideration of crop sensitivities and potential toxicity effects of the constituents in reclaimed water (see Sections 2.4 and 3.4.2) Reliability in quantity involves balancing supply with irrigation demand, largely accomplished by providing sufficient operational and seasonal storage facilities (see Sections 2.5 and 2.6.2).

It is also necessary to ensure that the irrigation system itself can reliably accept the intended supply to minimize the need for discharge or alternate disposal. In 1985 in Santa Rosa, California, the city exceeded its effluent discharge limits in part because the irrigation systems on the private farms were not able to distribute sufficient flows (Fox *et al.*, 1987).

In some cases, provisions may have to be made to supplement reclaimed water with another source to ensure that adequate supplies are available for peak demands. For example, to meet the occasional peak water demands associated with freeze protection of 27 citrus groves in the joint Orange County/Orlando, Florida Conserv II, water reuse program, 23 back-up irrigation wells were constructed, providing a peak well water flow of 51,000 gpm (3,220 L/s) (Cross *et al.*, 1992). The Walnut Valley Water District water reuse system in California also provides back-up wells to ensure demands can be met. As an interim solution until the wells went on line, two connections to the potable system were provided for emergency use (Cathcart and Biederman, 1984).

3.4.3.2 Site Use Control

Many states require a buffer zone around areas irrigated with reclaimed water. The size of this buffer zone is often associated with the level of treatment the reclaimed water has received and the means of application. Additional controls may include restrictions on the times irrigation can take place and restrictions on the access to the irrigated site. Such use area controls may require modification of existing farm practices and limit the use of reclaimed water to areas where required buffer zones can be provided. See Chapter 4 for a discussion of the different buffer zones and use controls specified in state regulations. Signs specifying that reclaimed water is being used may be required to prevent accidental contact or ingestion.

3.4.3.3 Monitoring Requirements

Monitoring requirements for reclaimed water use in agriculture differ by state (see Chapter 4). In most cases, the supplier will be required to sample the reclaimed water quality at specific intervals for specific constituents at the water reclamation plant and, in some cases, in the distribution system.

Groundwater monitoring is often required at the agricultural site, with the extent depending on the reclaimed water quality and the hydrogeology of the site. Groundwater monitoring programs may be as simple as a series of surficial wells to a complex arrangement of wells sampling at various depths. In locations of karst topography, where reclaimed water may percolate into underground sources of drinking water, reuse may be limited and in some cases prohibited.

Monitoring must be considered in estimating the capital and operating costs of the reuse system, and a complete understanding of monitoring requirements is needed as part of any cost/benefit analysis.

3.4.3.4 Runoff Controls

Some irrigation practices, such flood irrigation, result in a discharge of irrigation water from the site (tail water). Regulatory restrictions of this discharge may be few or none when using surface water or groundwater sources; however, when reclaimed water is used, runoff controls may be required to prevent discharge or a National Pollutant Discharge Elimination System (NPDES) permit may be required for a discharge to a surface water.

3.4.3.5 Marketing Incentives

In many cases, an existing agricultural site will have an established source of irrigation water, which has been developed by the user at some expense (e.g., engineering, permitting and construction). In some instances, the user may be reluctant to abandon these facilities for the opportunity to use reclaimed water. Reclaimed water use must then be economically competitive with existing irrigation practices or must provide some other benefits. For example, reclaimed water may extend an agricultural user's supply, allowing the user to expand production or plant a more valuable crop. Where irrigation is restricted as a water conservation measure in arid climates and during drought in other regions, reclaimed water can provide a dependable source for irrigation. Reclaimed water may also be of better quality than that water currently available to the farmer, and the nutrients may provide some fertilizer benefit.

In some instances, the supplier of reclaimed water may find it cost effective to subsidize reclaimed water rates to agricultural users if reuse is allowing the supplier to avoid higher treatment costs associated with alternative means of disposal. Rates and fees for reuse systems are discussed in Chapter 6.

Agricultural users will also expect assurance that reclaimed water will be beneficial to their crops and capable of producing a wholesome and valuable product. In some cases, a pilot project may be in order.

In the early 1980s, the Irvine Ranch Water District in Orange County, California, investigated the use of reclaimed water for the irrigation of strawberries. Field studies indicated that over the course of the season, yields for test and control plots were similar. However, the elevated concentrations of sodium and chloride in the reclaimed water resulted in reduced yields early in the season. Early season berries were being sold as fresh fruit for approximately $8.60/tray. The late season berries typically were frozen and sold for approximately $3.60/tray. Even with equal yield for the total season, the shifting of berry production from early to late season posed a marketing problem for this application (Hyde and Young, 1984).

3.4.3.6 Irrigation Equipment

By and large, few changes in equipment are required to use reclaimed water for agricultural irrigation. There are, however, some considerations for certain irrigation systems.

As previously noted, surface irrigation systems (ridge and furrow, graded borders) normally result in the discharge of a portion of the irrigation water from the site. Where discharge is not permitted with reclaimed water, some method of tailwater return or pump back may be required.

In sprinkler systems, dissolved salts and particulate matter may cause clogging, depending on the concentration of these constituents and the nozzle size. Studies in the Napa Sanitation District, California, indicated plugging of nozzles as small as 5/32-in (4-mm) diameter was not a serious problem with reclaimed water from an oxidation pond (Thornton *et al.*, 1984). In the Lubbock, Texas land treatment system, the use of a storage reservoir prior to irrigation greatly reduced nozzle clogging from trickling filter effluent. The quiescent reservoir allowed plastic fragments and other solid particles to settle out prior to irrigation. An unfortunate side effect of using the storage pond, however, was the loss of approximately 71 percent of the nitrogen value of the water (George *et al.*, 1984).

Because water droplets or aerosols from sprinkler systems are subject to wind drift, the use of reclaimed water may necessitate the establishment of buffer zones around the irrigated area. In some types of systems (i.e., center pivots), the sprinkler nozzles may be dropped closer to the ground to reduce aerosol drift and thus minimize the buffer requirements. In addition, sprinkler irrigation of crops to be eaten raw is restricted by some regulatory agencies as it results in the direct contact of reclaimed water with the fruit.

Micro-irrigation systems apply water at slow rates frequently, on or beneath the soil surface. Water is applied as drops, minute streams, or miniature sprays through closely spaced emitters attached to water delivery lines or via miniature spray nozzles. The conduits on which the emitters or miniature sprinklers are mounted are usually on the soil surface within the diameter of the root zone. The conduits may be buried at shallow depths or attached to trees for certain applications such as orchards. An extremely efficient form of irrigation, micro-irrigation systems are usually used in areas where water is scarce or expensive; soils are sandy, rocky, or difficult to level; or where crops require a high degree of soil moisture control.

When reclaimed water is used in a micro-irrigation system, a good filtration system is required to prevent complete or partial clogging of emitters, and close, regular inspections of emitters are required to detect emitter clogging. In-line filters of a 80 to 200 mesh are typically used to minimize clogging. In addition to clogging, biological growth within the transmission lines and at the emitter discharge may be increased by nutrients in the reclaimed water. Due to low volume application rates with micro-irrigation, salts may accumulate at the wetted perimeter of the plants and then be released at toxic levels to the crop when leached via rainfall.

3.5 Habitat Restoration/Enhancement and Recreational Reuse

Uses of reclaimed water for recreational and environmental purposes range from the maintenance of landscape ponds, such as water hazards on golf course fairways, to full-scale development of water-based recreational sites for swimming, fishing, and boating. In between lies a gamut of possibilities that includes ornamental fountains, snowmaking, rearing of freshwater sport fish, and the creation of marshlands to serve as wildlife habitat and refuges. As with any form of reuse, the development of recreational and environmental water reuse projects will be a function of a water demands coupled with a cost-effective source of reclaimed water of suitable quality.

As discussed in Chapter 4, many states have regulations specifically addressing recreational and environmental uses of reclaimed water. For example, California's recommended treatment train for each type of recreational water reuse is linked to the degree of body contact in that use (that is, to what degree swimming and wading are likely). Secondary treatment and disinfection to 2.2 total coliforms/100 mL is required for recreational water bodies where fishing, boating, and other non-body contact activities are permitted. And, for nonrestricted recreational use that includes wading and swimming, treatment of secondary effluent is to be followed by coagulation, filtration and disinfection to achieve 2.2 total coliforms/100 mL and a maximum of 23 total coliforms/100 mL in any one sample taken during a 30-day period. The primary purpose of the coagulation step is to reduce SS and, thereby, to improve the efficiency of virus removal by chlorination.

In California, approximately 7 percent of the total reuse within the state was associated with recreational and environmental reuse in 1987 (California State Water Resources Control Board, 1990). In Florida, approximately 9 percent of the reclaimed water currently produced is being used for environmental enhancements, all for wetlands restoration (Florida Department of Environmental Regulation, 1990).

The remainder of this section provides an overview of the following environmental and recreational uses:

- Creation or enhancement of wetlands habitat
- Recreational and aesthetic impoundments
- Stream augmentation
- Other recreational uses

The objectives of these reuse projects are typically to create an environment in which wildlife can thrive and/or to develop an area of enhanced recreational or aesthetic value to the community through the use of water.

3.5.1 Natural and Manmade Wetlands

Over the last 200 years, approximately 50 percent of the wetlands in the continental United States have been destroyed for such diverse uses as agriculture, mining, forestry, and urbanization. Approximately 109 million ac (44 million ha) of the original 215 million ac (87 million ha) of wetlands have been destroyed with an additional 370,000 to 555,000 (150,000 to 225,000 ha) destroyed each year (Hammer, 1989). Wetlands provide many worthwhile functions, including flood attenuation, wildlife and waterfowl habitat, productivity to support food chains, aquifer recharge, and water quality enhancement. In addition, the maintenance of wetlands in the landscape mosaic is important for the regional hydrologic balance. Wetlands naturally provide water conservation by regulating the rate of evapotranspiration and in some cases by providing aquifer recharge. The deliberate application of reclaimed water to wetlands can be a beneficial use (and therefore reuse) because the wetlands are maintained so that they may provide these valuable functions.

Reclaimed water has been applied to wetlands for three main objectives:

- To create, restore, and/or enhance wetlands systems;
- To provide additional treatment of reclaimed water prior to discharge to a receiving water body; and
- To provide a wet weather disposal alternative for a water reuse system (see Section 2.6.3).

For wetlands that have been altered hydrologically, application of reclaimed water serves to restore and enhance the wetlands. New wetlands can be created through application of reclaimed water, resulting in a net gain in wetland acreage and functions. In addition, manmade and restored wetlands can be designed and managed to maximize habitat diversity within the landscape.

The application of reclaimed water to wetlands is a good example of providing for compatible uses. Wetlands are often able to enhance the water quality of the reclaimed water without creating undesirable impacts to the wetlands system, thereby enhancing downstream natural water systems and providing concomitant aquifer recharge.

Water quality enhancement is provided by transformation and/or storage of specific components within the wetland. The maximum contact of reclaimed water within the wetland will ensure maximum nutrient assimilation. This is due to the nature of the assimilation process. If optimum conditions are maintained, nitrogen and BOD assimilation in wetlands will occur indefinitely, as they are primarily controlled by microbial processes. In contrast, phosphorus assimilation in wetlands is finite and is related to the adsorption capacity of the soil. The wetland will provide additional water quality enhancement to the high quality reclaimed water product.

In most reclaimed water to wetlands projects described in the literature, the primary intent is to provide additional treatment of effluent prior to discharge. However, this focus does not negate the need for design considerations that will maximize wildlife habitats, thereby resulting in an environmentally valuable system. Appropriate plant species should be selected based on the quality and quantity of reclaimed water applied to the wetland system. A salinity evaluation on any created wetlands should also be performed since highly saline wetlands often exhibit limited vegetative growth. Such design considerations will seek to balance the hydraulic and constituent loadings with the needs of the ecosystem. Protection of groundwater quality should also be considered.

Wetlands enhancement systems developed to provide wildlife habitats as well as treatment are illustrated by Arcata, California, and Orlando, Florida. In the Arcata program, one of the main goals of the project was the enhancement of the beneficial uses of the downstream surface waters. A wetlands application system was selected because the wetlands: (1) serve as nutrient sinks and buffer zones, (2) have aesthetic and environmental benefits, and (3) can provide cost-effective treatment through natural systems. The Arcata wetlands system was also designed to function as a wildlife habitat. The Arcata wetland system, consisting of three 10-ac (4-ha) marshes, has attracted more than 200 species of birds, provided a fish hatchery for salmon, and was a direct contributor to the development of the Arcata Marsh and Wildlife Sanctuary (Gearheart, 1988).

Due to a 20-mgd (877 L/s) expansion of the City of Orlando Iron Bridge Regional Water Pollution Control Facility in 1981, a wetland system was created to handle the additional flow. Since 1981, reclaimed water from the Iron Bridge Plant has been pumped 16 mi (20 km) to the wetland that was created by diking approximately 1,200 ac (480 ha) of improved pasture. The system is further divided into smaller cells for flow and depth management.

The wetland consists of three major vegetative areas. The first area, approximately 420 ac (170 ha), is a shallow marsh consisting primarily of cattails and bulrush and with nutrient removal as the primary function. The second area consists of 380 ac (150 ha) of a variety of mixed marsh species utilized for nutrient removal and wildlife habitat. The final area, 400 ac (160 ha) of hardwood swamp, consists of a variety of tree species providing nutrient removal and wildlife habitat. The reclaimed water then flows through approximately 600 ac (240 ha) of natural wetland prior to discharge to the St. Johns River (Lothrop, n.d.)

A number of states provide regulations which specifically address the use of reclaimed water in wetlands systems, including Arizona, Florida, and South Dakota. Where specific regulations are absent, wetlands have been constructed on a case-by-case basis. In addition to state requirements, natural wetlands, which are considered waters of the United States, are protected under EPA's NPDES Permit and Water Quality Standards programs. The quality of the reclaimed water entering natural wetlands is regulated by federal, state and local agencies and must be treated to at least secondary treatment levels or greater to meet water quality standards. Constructed wetlands, on the other hand, which are built and operated for the purpose of treatment only, are not considered waters of the United States. As a result, the application of primary effluent discharge into constructed wetlands to meet secondary effluent standards has been utilized in some instances.

3.5.2 Recreational and Aesthetic Impoundments

For the purposes of this discussion, an impoundment is defined as a manmade water body. The use of reclaimed water to augment natural water bodies is discussed in Section 3.5.3. Impoundments may serve a variety of functions from aesthetic, non-contact uses, to boating and fishing, to swimming. As with other uses of reclaimed water, the required level of treatment will vary with the intended use of the water. As the potential for human contact increases, the required treatment levels increase. The appearance of the reclaimed water must also be considered when used for impoundments, and treatment for nutrient removal may be required as a means of controlling algae. Without nutrient control there is a high potential for algae blooms, resulting in odors, an unsightly appearance, and eutrophic conditions. Phosphorous is generally the nutrient limited as a means of controlling algae in fresh water impoundments (Water Pollution Control Federation, 1989).

Reclaimed water impoundments can be easily incorporated into urban developments. For example, landscaping plans for golf courses and residential developments commonly integrate water traps or ponds. These same water bodies may also serve as a storage facilities for irrigation water within the site.

In Las Colinas, Texas, the design for a 12,000-ac (4,800 ha) master planned development included a series of manmade lakes [19 lakes covering 270 ac (110 ha)] for aesthetic enhancement. Lake levels are maintained with reclaimed water supplemented by water from the Elm Fork of the Trinity River. Six fountain type aerators were installed to enhance and maintain water quality (Smith *et al.*, 1990)

In Santee, California, reclaimed water has been used to supply recreational lakes for boating and fishing since 1961. Five lakes are served with reclaimed water with a total surface area of approximately 30 ac (12 ha). High nutrient levels in the reclaimed water promote algae and aquatic weed growth in the first two lakes; however, algae and other plant control through chemicals and mechanical harvesting is practiced. The lakes have become a part of a widely used and popular recreational area for local residents (Water Pollution Control Federation, 1989).

In Lubbock, Texas, approximately 4 mgd (175 L/s) of reclaimed water is used for recreational lakes in the Yellowhouse Canyon Lakes Park (Water Pollution Control Federation, 1989). The canyon, which was formerly used as a dump, was restored through the use of reclaimed water to provide water-oriented recreational activities. Four lakes, which include man-made waterfalls, are utilized for fishing, boating and water skiing; however, swimming is restricted.

The Tillman Water Reclamation Plant in Los Angeles, California is providing 8 mgd (350 L/s) of reclaimed water to fill the 26-ac (11-ha) Sepulveda Wildlife Lake. The Sepulveda Lake was created to provide a way station for migratory birds that travel through the Los Angeles area. A walking path has also been provided along the lake for wildlife viewing. Once the lake is filled, the amount of reclaimed water provided to the lake is reduced to 5 mgd (219 L/s) (Office of Water Reclamation - City of Los Angeles, 1991).

3.5.3 Stream Augmentation

Stream augmentation is differentiated from a surface water discharge in that augmentation seeks to accomplish a beneficial end, whereas discharge is primarily for disposal. Stream augmentation may be desirable to maintain stream flows and to enhance the aquatic and wildlife habitat as well as to maintain the aesthetic value of the watercourses. This may be necessary in locations where a significant volume of water is drawn for potable or other uses, significantly reducing the downstream volume of water in the river.

As with impoundments, the water quality requirements for stream augmentation will be based upon the designated use of the stream as well as the aim to maintain an acceptable appearance. In addition, there may be an emphasis on creating a product that can sustain aquatic life. To achieve aesthetic goals, studies in Kawasaki City, Japan, suggest that both phosphorus removal and high-level disinfection are required. However, to ensure that aquatic life is maintained, ozone is used in place of chlorine as a disinfectant (Kuribayashi, 1990).

In Japan, an appreciable amount of reclaimed water is being used for augmenting streams in urban areas and for creating ornamental streams and lakes (Murakami, 1989). Many streams and channels within urbanized Japanese cities dry up periodically as a result of changes in surrounding land use. Restoring these streams to productive water bodies has become important as people within the cities place more importance on a better environment. A typical project of this kind is illustrated by the restoration of the Nobidome and Tanagawa channels in metropolitan Tokyo. Originally constructed for water supply in the 17th century, these channels have lost all or most of their flow as a result of modern water transportation systems. The discharge of filtered secondary reclaimed water was begun in the early 1980s as a means of restoring these streams. Maintenance of the channels, primarily cleaning out trash and fallen leaves, is performed in cooperation with the local residents. The Nobidome receives approximately 4 mgd (175 L/s) and the Tanagawa approximately 3.5 mgd (153 L/s). Reaction from the surrounding urban population has been quite favorable (Murakami, 1989).

Several agencies in southern California are evaluating the process in which reclaimed water would be delivered to streams in order to maintain a constant high-quality flow of water for the enhancement of the aquatic and wildlife habitat as well as to maintain the aesthetic value of the streams. Reclaimed water delivered to these streams would also receive the benefit of additional treatment through natural processes (Crook, 1990).

3.5.4 Other Recreational Uses

Other recreational uses of reclaimed water that are beginning to gain recognition include the rearing of freshwater sport fish and snowmaking. Commercial fish production in reclaimed water impoundments is a widely used practice in Israel and China (Crook, 1990). Large-scale fish production with reclaimed water is currently being investigated in the United States and has the potential of providing a significant future use. Most recreational impoundments that utilize reclaimed water in the United States currently allow the use of fishing within the impoundment. When fish taken from an impoundment comprised entirely of reclaimed water are used for human consumption, the quality of the reclaimed water should be thoroughly assessed (chemical and microbiological quality) for possible bioaccumulation of toxic contaminants through the food chain.

The use of reclaimed water for snowmaking was originally studied as a means of storing effluent during winter when land application was not feasible. A study conducted at Steamboat Springs, Colorado, showed that snowmelt from reclaimed water has exhibited a substantial reduction in BOD and TSS (Smith, 1986). Reclaimed water for artificial snowmaking has been proposed as a method of supplementing snowmaking at ski resorts throughout New England. In Vermont, several experiments with using reclaimed water for snowmaking have been conducted; however at this time, no full-scale projects have been approved.

3.6 Groundwater Recharge

This section addresses planned groundwater recharge with reclaimed water with the specific intent to replenish groundwater. Although practices such as irrigation may contribute to groundwater augmentation, the replenishment is an incidental byproduct of the primary activity and is not discussed in this section.

The purposes of groundwater recharge using reclaimed water include: (1) to establish saltwater intrusion barriers in coastal aquifers, (2) to provide further treatment for future reuse, (3) to augment potable or nonpotable aquifers, (4) to provide storage of reclaimed water, or (5) to control or prevent ground subsidence.

Pumping of groundwater aquifers in coastal areas may result in seawater intrusion into the aquifers, making them unsuitable as sources of potable supply or for other uses where high salt levels are intolerable. A battery of injection wells and extraction wells can be used to create a hydraulic barrier to maintain intrusion control. Reclaimed water can be injected directly into a confined aquifer and subsequently extracted, if necessary, to maintain a seaward gradient and thus prevent inland subsurface seawater intrusion.

Infiltration and percolation of reclaimed water takes advantage of the subsoils' natural ability for biodegradation and filtration, thus providing additional *in situ* treatment of the wastewater and additional treatment reliability to the overall wastewater management system. The treatment achieved in the subsurface environment may eliminate the need for costly advanced wastewater treatment processes, depending on the method of recharge, hydrogeological conditions, requirements of the downstream users, and other factors. In some cases, the reclaimed water and groundwater blend and become indistinguishable.

Groundwater recharge helps provide a loss of identity between reclaimed water and groundwater. This loss of identity has a positive psychological impact where reuse is contemplated and is an important factor in making reclaimed water acceptable for a wide variety of uses, including potable water supply augmentation.

Groundwater aquifers provide a natural mechanism for storage and subsurface transmission of reclaimed water. Irrigation demands for reclaimed water are often seasonal, requiring either large storage facilities or alternative means of disposal when demands are low. In addition, suitable sites for surface storage facilities may not be available, economically feasible, or environmentally acceptable. Groundwater recharge eliminates the need for surface storage facilities and the attendant problems associated with uncovered surface reservoirs, such as evaporation losses, algae blooms resulting in deterioration of water quality, and creation of odors. Also, groundwater aquifers serve as a natural distribution system and may reduce the need for surface transmission facilities.

While there are obvious advantages associated with groundwater recharge, there are possible disadvantages to consider (Oaksford, 1985):

- Extensive land areas may be needed for spreading basins.
- Energy and injection wells for recharge may be prohibitively costly.

- Recharge may increase the danger of aquifer contamination. Aquifer remediation is difficult, expensive, and may take years to accomplish.
- Not all added water may be recoverable.
- The area required for operation and maintenance of a groundwater supply system (including the groundwater reservoir itself) is generally larger than that required for a surface water supply system.
- Sudden increases in water supply demand may not be met due to the slow movement of groundwater.
- Inadequate institutional arrangements or groundwater laws may not protect water rights and may present liability and other legal problems.

3.6.1 Methods of Groundwater Recharge

Recharge can be accomplished by riverbank or dune filtration, surface spreading, or direct injection.

3.6.1.1 Riverbank or Dune Filtration

Recharge via riverbank or sand dune filtration is practiced in Europe as a means of indirect potable reuse. It is incorporated as an element in water supply systems where the source is a contaminated surface water, usually a river. The contaminated water is infiltrated into the groundwater zone through the riverbank, percolation from spreading basins, or percolation from drain fields of porous pipe. In the latter two cases, the river water is diverted by gravity or pumped to the recharge site. The water then travels through an aquifer to extraction wells at some distance from the riverbank. In some cases, the residence time underground is only 20 to 30 days, and there is almost no dilution by natural groundwater (Sontheimer, 1980). In the Netherlands, dune infiltration of treated Rhine River water has been used to restore the equilibrium between fresh and saltwater in the dunes (Piet and Zoeteman, 1980), while serving to improve water quality and provide storage for potable water systems. Dune infiltration also provides protection from accidental spills of toxic contaminants into the Rhine River.

3.6.1.2 Surface Spreading

Surface spreading is a direct method of recharge whereby the water moves from the land surface to the aquifer by infiltration and percolation through the soil matrix.

An ideal soil for recharge by surface spreading would have the following characteristics:

- Rapid infiltration rates and transmission of water;
- No clay layers or other layers that restrict the movement of water to the desired unconfined aquifer;
- No expanding-contracting clays that create cracks when dried that would allow the reclaimed water to bypass the soil during the initial stages of the flooding period;
- Sufficient clay contents to provide large capacities to adsorb trace elements and heavy metals and to provide surfaces on which microorganisms decompose organic constituents; and
- A supply of available carbon that would favor rapid denitrification during flooding periods, support an active microbial population to compete with pathogens, and favor rapid decomposition of introduced organics (Pratt *et al.*, 1975). BOD and TOC in the reclaimed water will also be a carbon source.

Unfortunately, some of the above characteristics are mutually exclusive. The importance of each soil characteristic is dependent on the purpose of the recharge. For example, adsorption properties may be unimportant if recharge is primarily for storage.

After the applied recharge water has passed through the soil zone, the geologic and subsurface hydrologic conditions control the sustained infiltration rates. The following geologic and hydrologic characteristics should be investigated to determine the total usable storage capacity and the rate of movement of water from the spreading grounds to the area of groundwater draft:

- Physical character and permeability of subsurface deposits;
- Depth to groundwater;
- Specific yield, thickness of the deposits, and position and allowable fluctuation of the water table;
- Transmissivity, hydraulic gradients, and pattern of pumping; and
- Structural and lithologic barriers to both vertical and lateral movement of groundwater.

Although reclaimed water typically receives secondary treatment and disinfection (and in some cases, advanced wastewater treatment by filtration) prior to surface spreading, other treatment processes are sometimes provided. Depending on the ultimate use of the water and other factors (dilution, thickness of the unsaturated zone, etc.), additional treatment may be required. In soil-aquifer treatment systems where the extracted water is to be used for nonpotable purposes, satisfactory water quality has been obtained at some sites using primary effluent for spreading (Carlson *et al.*, 1982; Lance, *et al.*, 1980; Rice and Bouwer, 1984).

For surface spreading of the reclaimed water to be effective, the wetted surfaces of the soil must remain unclogged, the surface area should maximize infiltration, and the quality of the reclaimed water should not inhibit infiltration.

Operational procedures should maximize the amount of water being recharged while optimizing reclaimed water quality by maintaining an unsaturated (vadose) zone to take maximum advantage of treatment through the soil matrix. If infiltration is intended to improve water quality, as with rapid infiltration land treatment systems (EPA, 1981), the depth to the groundwater table should be deep enough to ensure continuous and effective removal of chemical and microbiological constituents.

Techniques for surface spreading include surface flooding, ridge and furrow systems, stream channel modifications, and infiltration basins. The system used is dependent on many factors such as soil type and porosity, depth to groundwater, topography, and the quality and quantity of the reclaimed water.

a. *Flooding*

Reclaimed water is spread over a large, gently sloped area (1 to 3 percent grade). Ditches and berms may enclose the flooding area. Advantages are low capital and O&M costs. Disadvantages are large areal requirements, evaporation losses, and clogging.

b. *Ridge and Furrow*

Water is placed in narrow, flat-bottomed ditches. Ridge and furrows are especially adaptable to sloping land, but only a small percentage of the land surface is available for infiltration.

c. *Stream Channel Modifications*

Berms are constructed in stream channels to retard the downstream movement of the surface water and, thus, increase infiltration into the underground. This method is used mainly in ephemeral or shallow rivers and streams, where machinery can enter the stream beds when there is little or no flow to construct the berms and prepare the ground surface for recharge. Disadvantages may include a frequent need for replacement due to washouts and possible legal restrictions related to such construction practices.

d. *Infiltration Basins*

Infiltration basins are the most widely used method of groundwater recharge. Basins afford high loading rates and relatively low maintenance and land requirements. Basins consist of bermed, flat-bottomed areas of varying sizes. Long, narrow basins built on land contours have been effectively used. Basins constructed on highly permeable soils to achieve high hydraulic rates are called rapid infiltration basins.

Rapid infiltration basins require permeable soil for high hydraulic loading rates, yet the soil must be fine enough to provide sufficient soil surfaces for biochemical and microbiological reactions, which provide additional treatment to the reclaimed water. Some of the best soils are in the sandy loam, loamy sand, and fine sand range.

When the reclaimed water is applied over to the spreading basin, the water percolates through the unsaturated zone to the saturated zone of the groundwater table. The hydraulic loading rate is preliminarily estimated by soil studies, but final evaluation is done by operating *in situ* test pits or ponds. Hydraulic loading rates for rapid infiltration basins vary from 65 to 500 ft (20 to 150 m)/yr, but are usually less than 300 ft (90 m)/yr (Bouwer, 1988).

Though management techniques are site specific and vary accordingly, some common principles are practiced in most systems. A wetting and drying cycle with periodic cleaning of the bottom is used to prevent clogging by accumulated SS, maintain a high rate of infiltration, maintain microbial populations to consume organic matter and help reduce levels of microbiological constituents in the reclaimed water, and promote nitrification and denitrification processes for nitrogen removal. The loading rates are usually higher when nitrogen removal is not a concern.

Spreading grounds can be managed to avoid nuisance conditions such as algae growth and insect breeding in the percolation ponds. Generally, a number of basins are rotated through filling, draining, and drying cycles. Cycle length is dependent on both soil conditions and the distance to the groundwater table and is determined on a case-by-case basis from field testing. Algae can clog the bottom of basins and reduce infiltration rates. Algae further aggravate soil clogging by removing carbon dioxide, which raises the pH, causing precipitation of calcium carbonate. Reducing the detention time of the

Table 20. Summary of Facilities and Management Practices for Percolation Recharge

Location	Load Rate (MG/ac/yr)	Perc. Rate (ft/d)	Load Schedule	Soil Type	Spreading Area Maintenance
Camp Pendelton, CA	N/A	8	As water becomes available	Coarse sand	Berm redevelopment, remove surface solids every other year
Hemet, CA	29	2.5	Fill 1 day (2.5-ft depth), drain 2 days, dry 1 day	Medium & coarse sand	Periodic rototilling of basins
Oceanside, CA	47	4.5	Fill to 3-ft depth, drain & dry, refill	Coarse sand	Basins scarified periodically
Phoeniz, AZ	137	2.5	Fill 10 days, dry 14 days	Loamy sand surface, coarse sand & gravel	Closely maintain flooding schedule, periodic scarifying
San Clemente, CA	140	5-10	Continuous	Coarse sand & gravel	None
St. Croix, Virgin Is.	36	1-2	Fill 18 days, dry 30 days	Silt, sand & clay	—
Whittier, CA	46	5-10	Fill 7 days (4-ft. depth), drain 7 days, dry 7 days	Sandy loam	Basins scarified periodically

Source: EPA, 1977.

reclaimed water within the basins minimizes algal growth. Also, scarifying, rototilling or discing the soil following the drying cycle can help alleviate clogging potential, although scraping or "shaving" the bottom to remove the clogging layer is more effective than discing it. Table 20 summarizes facilities and management practices for surface spreading operations at some sites in the U.S.

3.6.1.3 Soil-Aquifer Treatment Systems

Where hydrogeologic conditions permit groundwater recharge with surface infiltration facilities, considerable improvement in water quality may be obtained by movement of the wastewater through the soil, unsaturated zone, and aquifer. Table 21 provides an example of improvement in the quality of secondary effluent in a groundwater recharge soil-aquifer treatment (SAT) system. These data are the results of a demonstration project in the Salt River bed west of Phoenix, Arizona (Bouwer and Rice, 1984). The cost of SAT has been shown to be less than 40 percent of the cost of equivalent above-ground treatment (Bouwer, 1991).

SAT systems usually are designed and operated such that all of the infiltrated water is recovered via wells, drains, or seepage into surface water. Typical SAT recharge and recovery systems are shown in Figure 30. SAT systems with infiltration basins require unconfined aquifers, vadose zones free of restricting layers, and soils that are coarse enough to allow high infiltration rates but fine enough to provide adequate filtration. Sandy loams and loamy or fine sands are the preferred surface soils in SAT systems.

In the U.S., municipal wastewater usually receives conventional primary and secondary treatment prior to SAT. However, since SAT systems are capable of removing more BOD than is in secondary effluent (Bouwer, 1991), secondary treatment may not be necessary where the wastewater is subjected to SAT and subsequently reused for nonpotable purposes. The higher organic content of primary effluent may enhance nitrogen removal by denitrification in the SAT system (Lance *et al.*, 1980) and may enhance removal of synthetic organic compounds by stimulating greater microbiological activity in the soil (McCarty *et al*, 1984). A disadvantage of using primary effluent is that infiltration basin hydraulic loading rates may be lower than if higher quality effluent is used. This would require more frequent cleaning of the basins and increase the cost of the SAT, but not necessarily the total system cost.

Other methods of pretreatment prior to SAT may include lagoons or stabilization ponds, overland flow, or "natural" methods such as wetlands treatment. However, some of these low cost treatment methods may create infiltration

Table 21. Water Quality at Phoenix, Arizona SAT System

	Secondary effluent mg/L	Recovery well samples mg/L
Total dissolved solids	750	790
Suspended solids	11	1
Ammonium nitrogen	16	0.1
Nitrate nitrogen	0.5	5.3
Organic nitrogen	1.5	0.1
Phosphate phosphorus	5.5	0.4
Fluoride	1.2	0.7
Boron	0.6	0.6
Biochemical oxygen demand	12	<1
Total organic carbon	12	1.9
Zinc	0.19	0.03
Copper	0.12	0.016
Cadmium	0.008	0.007
Lead	0.082	0.066
Fecal coliforms/100 mL[a]	3500	0.3
Viruses, pfu/100 mL[b]	2118	<1

a Chlorinated effluent
b Undisinfected effluent

Source: Adapted from Bouwer and Rice, 1984.

problems if the water contains significant amounts of algae. The algae can form a filter cake or clogging layer on the bottom of the infiltration basins. To help alleviate this problem, the SAT infiltration basins should be shallow enough to avoid compaction of the clogging layer and to promote rapid turnover of the water in the basins (Bouwer and Rice, 1989).

3.6.1.4 Direct Injection

Direct injection involves the pumping of reclaimed water directly into the groundwater zone, which is usually a well-confined aquifer. Direct injection is used where groundwater is deep or where hydrogeological conditions are not conducive to surface spreading. Such conditions might include unsuitable soils of low permeability, unfavorable topography for construction of basins, the desire to recharge confined aquifers, or scarcity of land. Direct injection into a saline aquifer can create a freshwater "bubble," from which water can be extracted for reuse. Direct injection is also an effective method for creating barriers against saltwater intrusion in coastal areas.

Direct injection requires water of higher quality than surface spreading because of the absence of soil matrix treatment afforded by surface spreading and the need to maintain the hydraulic capacity of the confined aquifer. Treatment processes beyond secondary treatment that are used prior to injection include disinfection, filtration, air stripping, ion exchange, granular activated carbon, and reverse osmosis or other membrane separation processes. Using these processes, or various subsets in appropriate combinations, it is possible to satisfy all present water quality requirements for reuse.

For both surface spreading and direct injection, locating the extraction wells as great a distance as possible from the recharge site increases the flow path length and residence time in the underground, as well as the mixing of the recharged water with the natural groundwater (Todd, 1980).

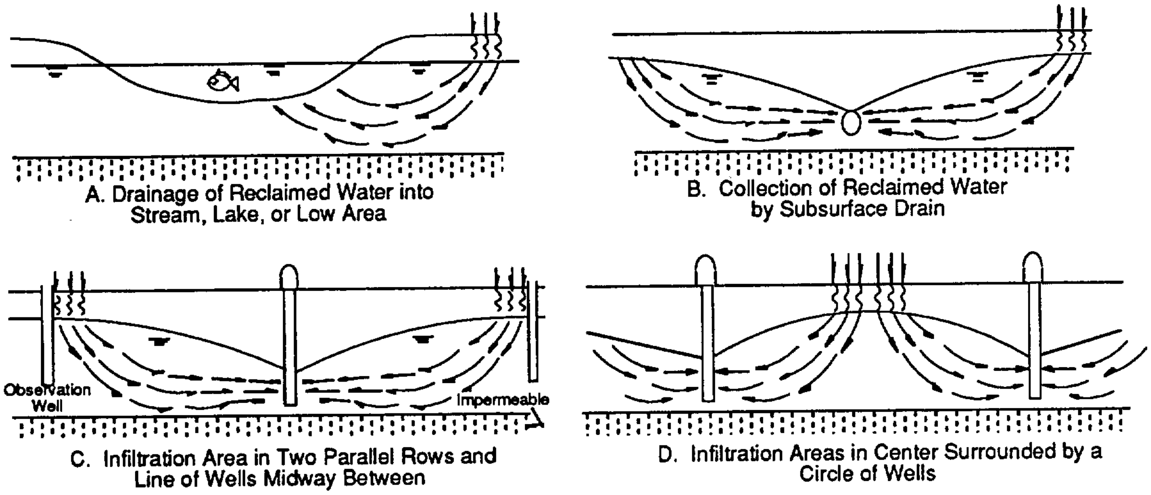
Ideally, an injection well will recharge water at the same rate as it can yield water by pumping. However, conditions are rarely ideal. Though clogging can easily by remedied in a surface spreading system by scraping, discing, drying and other methods, remediation in a direct injection system can be costly and time consuming. The most frequent causes of clogging are accumulation of organic and inorganic solids, biological and chemical contaminants, and dissolved air and gases from turbulence. Very low concentrations of SS, on the order of 1 mg/L, can clog an injection well. Even low concentrations of organic contaminants can cause clogging due to bacteriological growth near the point of injection.

There are many criteria specific to the quality of the reclaimed water, the groundwater, and the aquifer material that have to be taken into consideration prior to construction and operation. These include possible chemical reactions between the reclaimed water and the groundwater, iron precipitation, ionic reactions, biochemical changes, temperature differences, and viscosity changes (O'Hare, 1986). Most clogging problems are avoided by proper pretreatment and proper operation.

3.6.2 Fate of Contaminants in Recharge Systems

The fate of contaminants is an important consideration for groundwater recharge systems using reclaimed water. Contaminants in the subsurface environment are subject

Figure 30. Schematic of Soil-Aquifer Treatment Systems



Source: Bouwer, 1991.

to processes such as biodegradation by microorganisms, adsorption, filtration, ion exchange, volatilization, dilution, chemical oxidation and reduction, chemical precipitation and complex formation, and photochemical reactions (in spreading basins) (Roberts, 1980; EPA, 1989). For surface spreading operations, most of the removals of both chemical and microbiological constituents occur in the top 6 ft (2 m) of the vadose zone at the spreading site.

3.6.2.1 Particulate Matter

Particles larger than the soil pores are strained off at the soil-water interface. Particulate matter, including some bacteria, is removed by sedimentation in the pore spaces of the media during filtration. Viruses are mainly removed by adsorption. The accumulated particles gradually form a layer restricting further infiltration. Suspended solids that are not retained at the soil-water interface may be effectively removed by infiltration and adsorption in the soil profile. As water flows through passages formed by the soil particles, suspended and colloidal solids far too small to be retained by straining are thrown off the streamline through hydrodynamic actions, diffusion, impingent on, and sedimentation. The particles are then intercepted and adsorbed onto the surface of the stationary soil matrix. The degree of trapping and adsorption of suspended particles by soils is a function of the SS concentration, soil characteristics, and hydraulic loading (Chang and Page, 1979). Suspended solids removal is enhanced by longer travel distances underground.

For dissolved inorganic constituents to be removed or retained in the soil, physical, chemical, or microbiological reactions are required to precipitate and/or immobilize the dissolved constituents. In a groundwater recharge system, the impact of microbial activity on the attenuation of inorganic constituents is thought to be insignificant (Chang and Page, 1979). Chemical reactions that are important to a soil's capability to react with dissolved inorganics include cation exchange reactions, precipitation, surface adsorption, chelation, complexation, and weathering (dissolution) of clay minerals.

While inorganic constituents such as chloride, sodium, and sulfate are unaffected by ground passage, many other inorganic constituents exhibit substantial removal. For example, iron and phosphorus removals in excess of 90 percent have been achieved by precipitation and adsorption in the underground (Sontheimer, 1980; Idelovitch, *et al.*, 1980), although the ability of the soil to remove these and other constituents may decrease over time. Heavy metal removal varies widely for the different elements, ranging from 0 to more than 90 percent, depending on speciation of the influent metals.

Trace metals which normally occur in solution as anions (e.g., silver, chromium, fluoride, molybdenum, and selenium) are strongly retained by soil (Chang and Page, 1979; John, 1972). Boron, which is mainly in the form of undissociated boric acid in soil solutions, is rather weakly adsorbed and, given sufficient amounts of leaching water, most of the adsorbed boron is desorbed (Rhoades *et al.*, 1979). There are indications that once heavy metals are adsorbed, they are not readily desorbed, although desorption depends, in part, on buffer capacity, salt concentrations, and reduction-oxidation potentially (Sontheimer, 1980).

For surface spreading operations where an aerobic zone is maintained, ammonia is effectively converted to nitrates, but subsequent denitrification is dependent, in part, on anaerobic conditions during the flooding cycle and is often partial and fluctuating unless the system is carefully managed.

3.6.2.2 Dissolved Organic Constituents

Dissolved organic constituents are subject to biodegradation and adsorption during recharge. Biodegradation mainly occurs by microorganisms attached to the media surface. The rate and extent of biodegradation is strongly influenced by the nature of the organic substances and by the presence of electron acceptors such as dissolved oxygen and nitrate. There are indications that biodegradation is enhanced if the aquifer material is finely divided and has a high specific surface area, such as fine sand or silt. However, such conditions can lead to clogging by bacterial growths. Coarser aquifer materials such as gravel and some sands have greater permeability and, thus, less clogging, but biodegradation may be less rapid and perhaps less extensive (Roberts, 1980). The biodegradation of easily degradable organics occurs a short distance (few meters) from the point of recharge.

The end products of complete degradation under aerobic conditions include carbon dioxide, sulfate, nitrate, phosphate, and water, and the end products under anaerobic conditions include carbon dioxide, nitrogen, sulfide, and methane. The mechanisms operating on refractory organic constituents over long time periods typical of groundwater environments are not well understood. The degradation of organic contaminants may be partial and result in a residual organic product that cannot be further degraded at an appreciable rate.

Adsorption of organic constituents retards their movement (they can desorb and move chromatographically in the underground) and attenuates concentration fluctuations. Attenuation is a measure of the damping of organic constituent concentration fluctuations. The degree of attenuation increases with increasing adsorption strength, increasing distance from the recharge point, and increasing frequency of input fluctuation (Roberts, 1980). Recharged water may be free of many chemicals when it first appears at an extraction well, but the chemicals may begin to appear much later. Thus, chemical retardation needs to be evaluated when determining the effectiveness of contaminant removal in a recharge system (Bouwer, 1991).

Adsorption of uncharged organic compounds is believed to be related to the hydrophobic nature of compounds; highly chlorinated hydrocarbons are strongly adsorbed onto soils and, under typical recharge conditions, may be retained for many years (Roberts, 1980). Data reported by Sontheimer (1972) for riverbank infiltration along the Rhine River indicate that organic removal efficiency in bank filtration decreased as the relative amount of chlorine in the molecule increased. Studies involving sand dune filtration in the Netherlands indicated that the haloforms and organic nitrogen compounds were readily removed during passage through the dunes (Piet and Zoeteman, 1980).

In one study involving rapid infiltration of secondary effluent, nonhalogenated aliphatic and aromatic hydrocarbons and the priority pollutants ethylbenzene, napthalene, phenanthene, and diethylphthalate exhibited a concentration decrease between 50 and 99 percent during soil percolation, but many of the compounds could still be detected in the underlying groundwater (Bouwer, *et al.*, 1984). Smaller reduction in concentrations of the halogenated organic compounds and organic substances represented by total organic halogen were observed with soil passage compared to the specific nonhalogenated organic compounds found in the basin water. Another study indicated that nonvolatile organic halogens in injected reclaimed water were not retarded during passage through the ground, but that 50 percent were removed, presumably due to microbial degradation (Reinhard, 1984). Table 22 indicates the variability in different constituent removals after 2.5 m (8 ft) of percolation at a spreading basin.

3.6.2.3 Microorganisms

The survival or retention of pathogenic microorganisms in the subsurface is dependent on several factors, including climate, soil composition, antagonism by soil microflora, flow rate, and type of microorganism. At low temperatures (below 4°C [39°F]) some microorganisms can survive for months or years. The die-off rate is approximately doubled with each 10°C rise in temperature between 5 and 30°C (41 and 86°F) (Gerba and Goyal, 1985). Rainfall may mobilize bacteria and viruses that had been filtered or adsorbed and thus enhances their transport (Wellings *et al.*, 1975).

The nature of the soil affects survival and retention. For example, rapid infiltration sites at which viruses have been detected in groundwater were located on coarse sand and gravel types. Infiltration rates at these sites were high, and the ability of the soil to adsorb the viruses was low. Generally, coarse soil does not inhibit virus migration (EPA, 1981). Other soil properties, such as pH, cation concentration, moisture holding capacity, and organic

Table 22. Results of Test Basin Sampling Program at Whittier Narrows, California

Constituent	Average Concentration At Surface	Average Concentration At 8 ft (2.5 m)	Linear Trend	Significance[a]
Total hardness (mg $CaCO_3$/L)	202	373	Increasing	<0.001
Total dissolved solids (mg/L)	516	703	Increasing	<0.001
Ammonia (mg/L)	14.6	0.25	Decreasing	<0.001
Nitrate (mg/L)	0.91	8.52	Increasing	0.009
Nitrite (mg/L)	0.86	0.02	Decreasing	<0.001
COD (mg/L)	29.3	12.3	Decreasing	<0.001
TOC (mg/L)	10.15	3.43	Decreasing	<0.001
Methylene chloride (μg/L)	16.9	1.9	Decreasing	0.026
Chloroform (μg/L)	5.2	2.5	Decreasing	0.008
Trichloroethylene (μg/L)	2.7	3.8	Increasing	NS[b]
Tetrachloroethylene (μg/L)	2.3	1.0	Decreasing	0.019

[a]Level of significance based on two-tailed *t*-test.
[b]Not significant ($p>0.05$)

Source: Nellor *et al.*, 1985.

matter affect the survival of bacteria and viruses in the soil (Gerba and Lance, 1980). Resistance of microorganisms to environmental factors depends on the species and strains present.

Drying of the soil will kill both bacteria and viruses. Bacteria survive longer in alkaline soils than in acid soils (pH 3 to 5) and when large amounts of organic matter are present (Gerba, Wallis, and Melnick, 1975). In general, increasing cation concentration and decreasing pH and soluble organics tend to promote virus adsorption. Bacteria and larger organisms associated with wastewater are effectively removed after percolation through a short distance of the soil mantle. Factors that may influence virus movement in groundwater are given in Table 23. Viruses have been isolated by a number of investigators examining a variety of recharge operations, after various migration distances. These are summarized in Table 24. Proper treatment (including disinfection) prior to recharge, site selection, and management of the surface spreading recharge system can minimize or eliminate the presence of microorganisms in the groundwater.

3.6.3 Health and Regulatory Considerations

The constraints on recharge are conditioned by the use to which the abstracted water will be put, and include health concerns, economic feasibility, physical limitations, legal restrictions, water quality constraints, and reclaimed water availability. Of these constraints, the health concerns are the most important as they pervade almost all recharge projects. Where there is to be ingestion of the reclaimed water, health effects due to prolonged exposure to low levels of contaminants must be considered as well as the acute health effects from pathogens or toxic substances. [See Section 2.4 Health Assessment and Section 3.7 Augmentation of Potable Supplies.]

One problem with recharge is that boundaries between potable and nonpotable aquifers are rarely well defined. Some risk of contaminating high quality potable groundwater supplies is often incurred by recharging "nonpotable" aquifers. The recognized lack of knowledge about the fate and long-term health effects of contaminants found in reclaimed water obliges a conservative approach in setting water quality standards for groundwater recharge. In light of these uncertainties, some states have set stringent water quality requirements and require high levels of treatment—in some cases organics removal processes—where recharge affects potable aquifers.

3.7 Augmentation of Potable Supplies

Table 23. Factors that May Influence Virus Movement to Groundwater

Factor	Comments
Soil type	Fine-textured soils retain viruses more effectively than light-textured soils. Iron oxides increase the adsorptive capacity of soils. Muck soils are generally poor adsorbents.
pH	Generally, adsorption increases when pH decreases. However, the reported trends are not clear-cut due to complicating factors.
Cations	Adsorption increases in the presence of cations (cations help reduce repulsive forces on both virus and soil particles). Rainwater may desorb viruses from soil due to its low conductivity.
Soluble organics	Generally compete with viruses for adsorption sites. No significant competition at concentrations found in wastewater effluents. Humic and fulvic acids reduce virus adsorption to soils.
Virus type	Adsorption to soils varies with virus type and strain. Viruses may have different isoelectric points.
Flow rate	The higher the flow rate, the lower virus adsorption to soils.
Saturated vs. unsaturated flow	Virus movement is less under unsaturated flow conditions.

Source: Gerba and Goyal, 1985.

Table 24. Isolation of Viruses Beneath Land Treatment Sites

Site Location	Site Type[a]	Maximum Distance of Virus Migration (m) Depth	Horizontal
St. Petersburg, FL	S	6.0	—
Gainesville, FL	S	3.0	7
Lubbock, TX	S	30.5	—
Kerrville,TX	S	1.4	—
Muskegon, MI	S	10.0	—
San Angelo, TX	S	27.5	—
East Meadow, NY	R	11.4	3.0
Holbrook, NY	R	6.1	45.7
Sayville, NY	R	2.4	3
12 Pines, NY	R	6.4	—
North Masapequa,NY	R	9.1	—
Babylon, NY	R	22.8	408
Ft. Devens, MA	R	28.9	183
Vineland, NJ	R	16.8	250
Lake George, NY	R	45.7	400
Phoenix, AZ	R	18.3	3
Dan Region, Israel	R	31-67	60-270

[a]S = Slow-rate infiltration, R = Rapid infiltration.
Source: Adapted from Gerba and Goyal, 1985.

Water is a renewable resource. It is cleansed and reused continually, powered by solar energy in the hydrological cycle. The distillate produced, rainfall, is pure, until it picks up contaminants as it falls through the atmosphere and flows over and through the ground and in rivers and lakes polluted by urban, industrial, and agricultural discharges.

A principle that has guided the development of potable water supplies for almost 150 years was stated in the 1962 Public Health Service Drinking Water Standards: ". . . water supply should be taken from the most desirable source which is feasible, and efforts should be made to prevent or control pollution of the source." This was affirmed by EPA (1976) in its Primary Drinking Water Regulations: ". . . priority should be given to selection of the purest source. Polluted sources should not be used unless other sources are economically unavailable. . ."

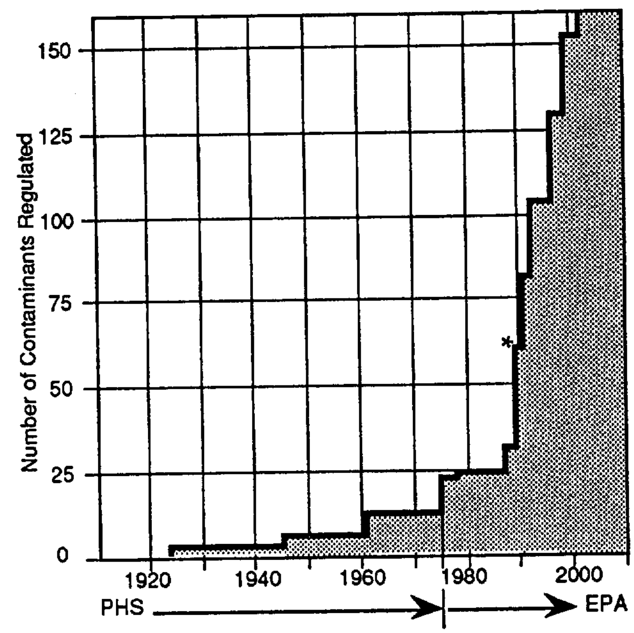
This section discusses indirect potable reuse, where treated wastewater is discharged into a water course or underground and withdrawn downstream or downgradient at a later time for potable purposes, and direct potable reuse, where the reclamation plant effluent is piped into the potable water system. Both such sources of potable water are, on their face, less desirable than using a higher quality source for drinking.

3.7.1 *Water Quality Objectives for Potable Reuse*

Whereas the water quality requirements for nonpotable urban reuse are quite tractable and treatment requirements are not likely to change significantly in the future, drinking water quality standards will become more rigorous in the future, requiring more and more treatment for potable reuse. The number of contaminants regulated, by the Public Health Service until 1974 and subsequently by the EPA, has grown from a handful in 1925 to a target of more than 100 as shown in Figure 31. Not only are the numbers of contaminants to be monitored increasing, but, for many of them, the maximum contaminant limits (MCLs) are decreasing. For example, the MCL for lead was reduced in 1992 from 50 ug/L to an action level of 15 ug/L. The health effects for many of the individual regulated contaminants are not well established.

It is estimated that only about 10 percent by weight of the organic compounds in drinking water have been identified (National Research Council, 1980) and the health effects of only a few of the individual identified compounds have been determined (National Research Council, 1980). The health effects of mixtures of two or more of the hundreds of compounds in any single source of drinking water drawn from wastewater will not be easily characterized. Health effects studies for reuse are applicable only to the specific situation, as the contaminant mix varies from city to city. Also, for any one city, it is likely that the contaminants will change over the years.

Figure 31. Number of Drinking Water Contaminants Regulated by the U.S. Government



*From this date, requirements of Safe Drinking Water Act and its amendments

Some organic compounds, particularly chlorinated species, are known or suspected carcinogens. Many epidemiological studies have been conducted to assess the potential health effects associated with drinking water derived from sources containing significant amounts of wastewater. The results have generally been inconclusive, although they provided sufficient evidence for maintaining a hypothesis that there may be a health risk (National Research Council, 1980). One study, conducted by the National Cancer Institute, indicated an increased incidence of bladder cancer in people who drank chlorinated surface water as compared to those who drank unchlorinated groundwater (Cantor *et al.*, 1987). Recognizing the limitations of epidemiological studies because of the many compounding variables, these studies — and the earlier research on drinking water taken from the Mississippi River that led to initial passage of the Safe Drinking Water Act — do provide a basis for concern where water that may contain significant levels of organic constituents is subsequently chlorinated and distributed for potable use. In general, the poorer the raw water quality, the more chlorine is required and the greater is the resulting risk.

Quality standards have been established for many inorganic constituents and treatment and analytical technology has demonstrated our capability to identify, quantify, and control these substances. Similarly, available technology is capable of eliminating pathogenic agents from contaminated waters. However, unanswered questions remain with organic constituents, due mainly to their potential large number and unresolved health risk potential resulting from long-term exposure to extremely low considerations.

3.7.2 Indirect Potable Water Reuse

Many cities have elected in the past to take water from large rivers that receive substantial wastewater discharges because of the assurance that conventional filtration and disinfection will eliminate the pathogens responsible for water-borne infectious disease. These supplies were generally less costly and were more easily developed than upland supplies or underground sources. Such large cities as Philadelphia, Cincinnati, and New Orleans, drawing water from the Delaware, Ohio and Mississippi Rivers, respectively, are thus practicing indirect potable water reuse. The many cities upstream of their intakes can be characterized as providing water reclamation in their wastewater treatment facilities, although they were not designed, nor are they operated, as potable water sources. NPDES permits for these discharges are intended to make the rivers "fishable and swimmable," and generally do not reflect potable water requirements downstream. These indirect potable reuse systems originated at a time when the principal concern for drinking water quality was the prevention of enteric infectious diseases. Nevertheless, most cities do provide water of acceptable quality that meets current drinking water regulations.

More recent indirect potable reuse projects are exemplified by the Upper Occoquan Sewage Authority (UOSA) treatment facilities in northern Virginia, which discharge reclaimed water into the Bull Run just above Occoquan Reservoir, a source of water supply for Fairfax County, Virginia, and the Clayton County, Georgia, project where wastewater, following secondary treatment, undergoes land treatment, with the return subsurface flow reaching a stream used as a source of potable water. The UOSA plant provides AWT (Robbins and Ehalt, 1985) that is more extensive than required treatment for nonpotable reuse and accordingly provides water of much higher quality for indirect potable reuse than is required for nonpotable reuse.

While UOSA now provides a significant portion of the water in the system, varying from an average of about 10 percent of the total flow to as much as 40 percent in low flow periods, most surface indirect potable reuse projects have been driven by requirements for wastewater disposal and pollution control; their contributions to increased public water supply were incidental. In a comprehensive comparative study of the Occoquan and Clayton County projects, the water quality parameters assessed were primarily those germane to wastewater disposal and not to drinking water (Reed and Bastian, 1991). Most discharges that contribute to indirect potable water reuse, especially via rivers, are managed as wastewater disposal functions and are handled in conformity with practices common to all water pollution control efforts. The abstraction and use of the reclaimed water is almost always the responsibility of a water supply agency that is not at all related politically, administratively or even geographically, except for being downstream, to the wastewater disposal agency.

While direct potable reuse is not likely to be adopted soon, indirect potable reuse via surface waters has been, and will continue to be, practiced widely. Issues evolving from these practices are the substance of extensive studies of water pollution control and water treatment, resulting in a large number of publications and regulations that do not require elucidation in this document. Indirect potable reuse via groundwater recharge is being practiced to a lesser extent.

3.7.3 Groundwater Recharge for Potable Reuse

As mentioned in Section 3.6.1., Methods of Groundwater Recharge, groundwater recharge via riverbank or sand dune filtration, surface spreading, or injection has long been used to augment potable aquifers. Riverbank or dune filtration of untreated surface water is distinctly different from recharge of highly treated wastewater, but the health concerns associated with this practice are similar to those for potable reuse generally. Riverbank or dune filtration includes infiltrating river water into the groundwater zones through the riverbank, percolation from spreading basins, or percolation from drain fields or porous pipe. In the latter two cases, the river water is diverted by gravity or pumped to the recharge site. The water then travels through an aquifer to extraction wells at some distance from the riverbank. In some cases, the residence time underground is only 20 to 30 days, and there is almost no dilution by natural groundwater (Sontheimer, 1980). In the Netherlands, dune infiltration of treated Rhine River water has been used to restore the equilibrium between fresh and saltwater in the dunes (Piet and Zoeteman, 1980), while serving to improve water quality and provide storage for potable water systems.

Dune infiltration also provides protection from accidental spills of toxic contaminants into the Rhine River.

Although both planned and unplanned recharge into potable aquifers has occurred for many years, few health-related studies have been undertaken. The most comprehensive health effects study of an existing groundwater recharge project was carried out in Los Angeles County in response to uncertainties about the health consequences of recharge for potable use raised by a California Consulting Panel in 1975-76.

In 1978, the Sanitation Districts of Los Angeles County initiated a 5-year, $1.4 million, study of the Montebello Forebay Groundwater Recharge Project at Whittier Narrows that had been replenishing groundwater with reclaimed water since 1962. Three water reclamation plants provide water for the spreading operation. The plants provide secondary treatment (activated sludge), dual-media filtration (Whittier Narrows and San Jose Creek) or activated carbon filtration (Pomona), disinfection with chlorine, and dechlorination. By 1978, the amount of reclaimed water spread averaged about 9 billion gal/yr (34 x 10^3 m^3/yr) or 16 percent of the total inflow to the groundwater basin with no more than about 8 billion gal (42 x 10^6 x m^3) of reclaimed water spread in any year. The percentage of reclaimed water contained in the extracted potable water supply ranged from 0 to 11 percent on a long-term (1962-1977) basis (Crook *et al.*, 1990).

Historical impacts on groundwater quality and human health and the relative impacts of the different replenishment sources-reclaimed water, stormwater runoff, and imported surface water-on groundwater quality were assessed after conducting a wide range of research tasks, including:

- Water quality characterizations of groundwater, reclaimed water, and other recharge sources in terms of their microbiological and inorganic chemical content;
- Toxicological and chemical studies of groundwater, reclaimed water and other recharge sources to isolate and identify health-significant organic constituents;
- Percolation studies to evaluate the efficacy of soil in attenuating inorganic and organic chemicals in reclaimed water;
- Hydrogeological studies to determine the movement of reclaimed water through groundwater and the relative contribution of reclaimed water to municipal water supplies; and,
- Epidemiological studies of populations ingesting reclaimed water to determine if their health characteristics differ significantly from a demographically similar control population.

The study's results indicated that the risks associated with the three sources of recharge water were not significantly different and that the historical proportion of reclaimed water used for replenishment had no measurable impact on either groundwater quality or human health (Nellor, *et al.*, 1984). The health effects study did not demonstrate any measurable adverse effects on the area's groundwater or the health of the population ingesting the water. The cancer-related epidemiological study findings are somewhat weakened by the fact that the minimal observed latency period for human cancers that have been linked to chemical agents is about 15 years, and may be much longer. Because of the relatively short time period that groundwater containing reclaimed water has been consumed, it is unlikely that examination of cancer mortality rates would have detected an effect of exposure to reclaimed water resulting from the groundwater recharge operation, even if an effect were present (State of California, 1987).

Groundwater recharge has inherent disadvantages not present with indirect surface water reuse. If water of poor quality is discharged to a river, the river can be expected to be cleansed when the pollution is stopped. If poor quality water is charged into an aquifer and found later to be troublesome, cleansing the aquifer will be costly and difficult.

3.7.4 Direct Potable Water Reuse

Pipe-to-pipe water reclamation and direct potable reuse is currently practiced in only one city in the world, Windhoek, Namibia, and there only intermittently. In the U.S., the most extensive research focusing on direct potable reuse has been conducted in Denver, Colorado; Tampa, Florida; and San Diego, California. A considerable investment in potable reuse research has been made in Denver, Colorado, over a period of more than 20 years, which included operation of a 1-mgd (44-L/s) reclamation plant in many different process modes over a period of about 10 years (Lauer, 1991). The product water was reported to be of better quality than many potable water sources in the region and certainly better than what is produced by many purveyors of drinking water elsewhere in the country who use run-of-river sources. Table 25 illustrates the high quality of the product water produced by the demonstration plant, to the extent revealed by the parameters monitored. Health

Table 25. Test Results, Denver Potable Water Reuse Demonstration Project (Geometric Mean Values, Jan. 9 to Dec. 31, 1989)

Parameter (mg/l unless indicated)	MCL	RO	UF
General			
Total Alkalinity	—	3	166
Hardness	—	6	108
TSS	—	*	*
TDS	500	18	352
Specific Conductance (umhos/cm)	—	67	648
pH	6.5 - 8.5	6.6	7.8
DO	—	8.3	6.9
Temperature - °C	—	21	21
Turbidity - NTU	1.0	0.06	0.2
TOC	—	*	0.7
Color	15	*	*
Particle Size > 128 µm (count/50 ml)	—	*	*
Particle Size 64-128 µm (count/50 ml)	—	*	*
Particle Size 32-64 µm (count/50 ml)	—	1.2	18
Particle Size 16-32 µm (count/50 ml)	—	58	100
Particle Size 8-16 µm (count/50 ml)	—	147	448
Particle Size 4-8 µm (count/50 ml)	—	219	1290
Asbestos - million fibers/l	7	*	*
MBAS	0.5	*	*
TOX	—	8	23
Radiological			
Gross Alpha - pCi/l	15	*	*
Gross Beta - pCi/l	50	*	6
Radium 228 - pCi/l	5	*	*
Radium 226 - pCi/l	5	*	*
Tritium - pCi/l	20,000	*	37
Radon - pCi/l	—	*	*
Plutonium - pCi/l	—	*	*
Microbiological			
m-HPC (count/ml)	—	*	350
Total Coliform (count/100 ml)	1	*	*
Fecal Strep (count/100 ml)	—	*	*
Fecal Coliform (count/100 ml)	—	*	*
Shigella	—	*	*
Salmonella	—	*	*
Clostridium	—	*	*
Campylobacter	—	*	*
Coliphage B (pfu/100 ml)	—	*	*
Coliphage C (pfu/100 ml)	—	*	*
Giardia (cysts/l)	—	*	*
Endamoeba coli (cysts/l)	—	*	*
Nematodes (count/l)	—	*	*
Algae (count/ml)	—	*	*
Enteric Virus	—	*	*
Entamoeba histolytica (cysts/l)	—	*	*
Cryptosporidium (oocysts/l)	—	*	*
Inorganic			
Aluminum	—	*	*
Arsenic	0.05	*	*
Boron	—	0.2	0.3
Bromide	—	*	*
Cadmium	0.01	*	*
Calcium	—	1	38
Chloride	250	19	96
Chromium	0.05	*	*
Copper	1	0.009	0.01
Cyanide	0.2	*	0.03
Fluoride	2	*	0.78
Iron	0.3	0.02	0.07
Potassium	—	0.7	9.1
Magnesium	—	0.1	1.8
Manganese	0.05	*	*
Mercury	0.002	*	*
Molybdenum	—	*	0.004
TKN	—	5	19
Ammonia-N	—	5	19
Nitrate-N	10	0.1	0.3
Nitrite-N	1	*	*
Nickel	0.1	*	*
Inorganic (continued)			
Total Phosphate-P	—	0.02	0.05
Selenium	0.01	*	*
Silica	—	2	8.8
Strontium	—	*	0.13
Sulfate	250	1	58
Lead	0.05	*	*
Uranium	—	*	*
Zinc	5	0.006	0.016
Sodium	—	4.8	78
Lithium	—	*	0.014
Titanium	—	*	0.035
Barium	1.0	*	*
Silver	0.05	*	*
Rubidium	—	*	0.003
Vanadium	—	*	*
Iodine	—	*	0.002
Antimony	—	*	*
Thallium	0.002	*	*

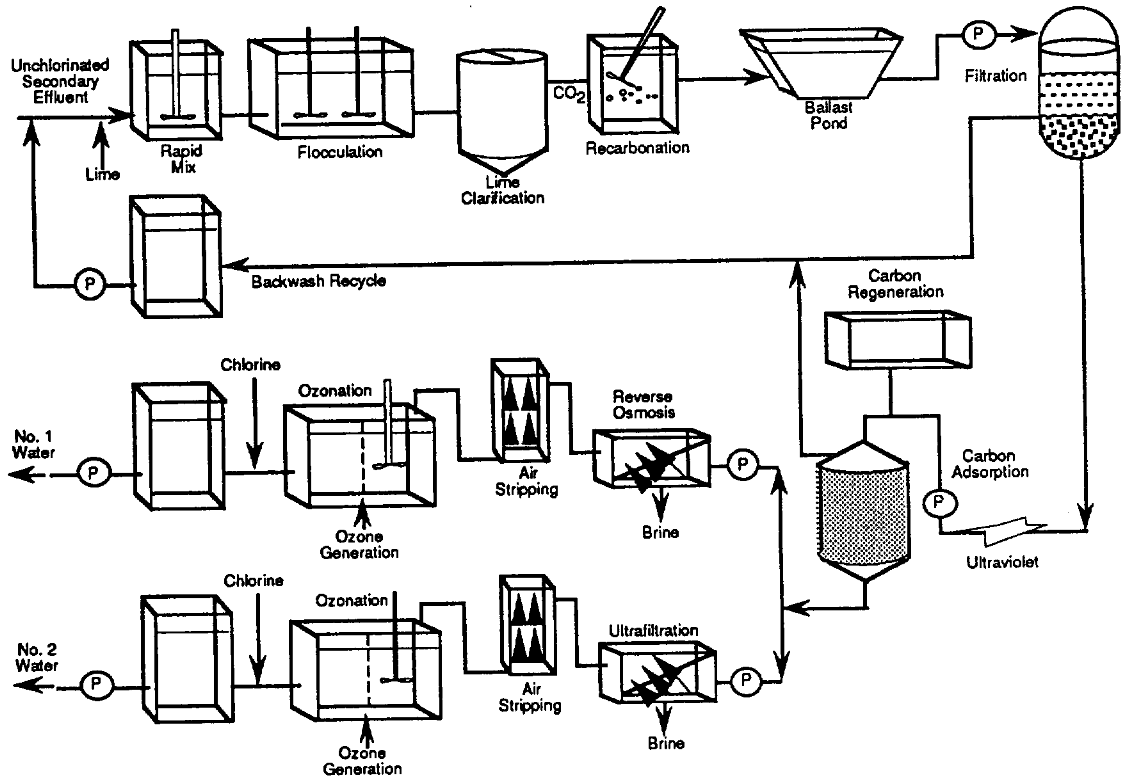
Test Method	Number of Tests UF	Number of Tests RO	Comments
EPA 502.2	47	53	No compounds detected
Grob Closed Loop Stripping GC/MS (EPA 8270)	44	48	No compounds detected
Carbamate Pesticides (EPA - 531)	2	2	No compounds detected
Pesticides (EPA 508) + (EPA 608)	5	5	No compounds detected
Herbicides (EPA 515.1)	5	5	No compounds detected
Polychlorinated Biphenyls (EPA 504)	3	3	No compounds detected
Polynuclear Aromatic Hydrocarbons (EPA 610)	3	3	No compounds detected
Base Neutral & Acid Extractables (EPA 625)	3	4	No compounds detected
Haloacetic Acids**	3	4	No compounds detected
Pentane Extractable Disinfection Byproducts**	3	4	No compounds detected
Aldehydes**	2	2	UF contained: 7 µg/l acetaldehyde and 13 µg/l formaldehyde RO contained: no aldehydes

NOTES:

MCL = EPA Maximum Contaminant Level for drinking water at time of testing.
RO = Reuse product treated by processes in Figure 32 including reverse osmosis.
UF = Reuse product treated by processes in Figure 32 including ultrafiltration.
— = No MCL established at time of testing.
* = More than 50% of data below detection limit.
** = Montgomery Laboratory Methods (Pasadena, California).

Source: Hamaan *et al.*, 1992.

Figure 32. Denver Potable Reuse Demonstration Treatment Processes



Source: Adapted from Lauer, 1991.

effects and toxicity studies were also carried out, but the results are not yet available. Field work was completed in 1990, but there are no immediate plans to implement direct or indirect potable reuse in Denver.

Representative of the treatment train required for direct potable reuse is that developed in Denver. It includes, after secondary treatment, the following processes, as shown in Figure 32:

- High-pH lime clarification,
- Recarbonation,
- Multimedia filtration,
- Ultraviolet disinfection (as an option),
- Activated carbon adsorption,
- Reverse osmosis or ultrafiltration (as alternative options),
- Air stripping,
- Ozonation, and
- Chlorination

Most of these unit processes are well understood and their performance can be expected to be effective and reliable in large, well-managed plants. However, the heavy burden of sophisticated monitoring for trace contaminants that is required for potable reuse may be beyond the capacity of smaller enterprises.

Despite the generally excellent results achieved in Denver, there are no immediate plans to implement potable reuse there. The implementation of direct, pipe-to-pipe, potable reuse is not likely to be adopted in the foreseeable future in the U.S. or elsewhere for several reasons:

- Many attitude surveys show that the public will accept and endorse many types of nonpotable reuse while being reluctant to accept potable reuse. In general, the public's reluctance to support reuse increases as the degree of human contact with the reclaimed water increases. Section 7.3 includes a discussion of public perceptions about reuse.

- Indirect potable reuse is more acceptable to the public than direct potable reuse because the water is perceived to be "laundered" as it moves in a river, lake, or aquifer. Whittier Narrows and El

Paso are examples. Indirect reuse, by virtue of the residence time in the water course, reservoir or aquifer, often provides additional treatment and offers an opportunity for monitoring the quality and taking appropriate measures before the water is abstracted for distribution. In some instances, however, water quality may actually be degraded as it passes through the environment.

- ❑ Direct potable reuse will seldom be necessary. Only a small portion of the water used in a community needs to be of potable quality. While high quality sources will often be inadequate to serve all urban needs in the future, the substitution of reclaimed water for potable quality water now used for nonpotable purposes would release more of the high quality water service for potable purposes.

3.8 Case Studies

3.8.1 Pioneering Urban Reuse for Water Conservation: St. Petersburg, Florida

The City of St. Petersburg, Florida, is recognized as a pioneer in urban water reuse. Faced with the alternatives of ceasing effluent discharges to Tampa Bay or upgrading to advanced wastewater treatment, the city council adopted a policy of "zero discharge" in 1977, and in 1978 St. Petersburg began distributing reclaimed water for nonpotable uses via an urban dual distribution system.

Today, St. Petersburg operates one of the largest urban reuse systems in the world, providing reclaimed water to more than 7,000 residential homes and businesses. In 1991, the city provided approximately 21 mgd (920 L/s) of reclaimed water for irrigation of individual homes, condominiums, parks, school grounds, and golf courses; cooling tower make-up; and supplemental fire protection.

Four wastewater treatment plants, with a total combined capacity of 68.4 mgd (3,000 L/s), provide activated sludge secondary treatment, followed by alum coagulation, filtration, and disinfection.

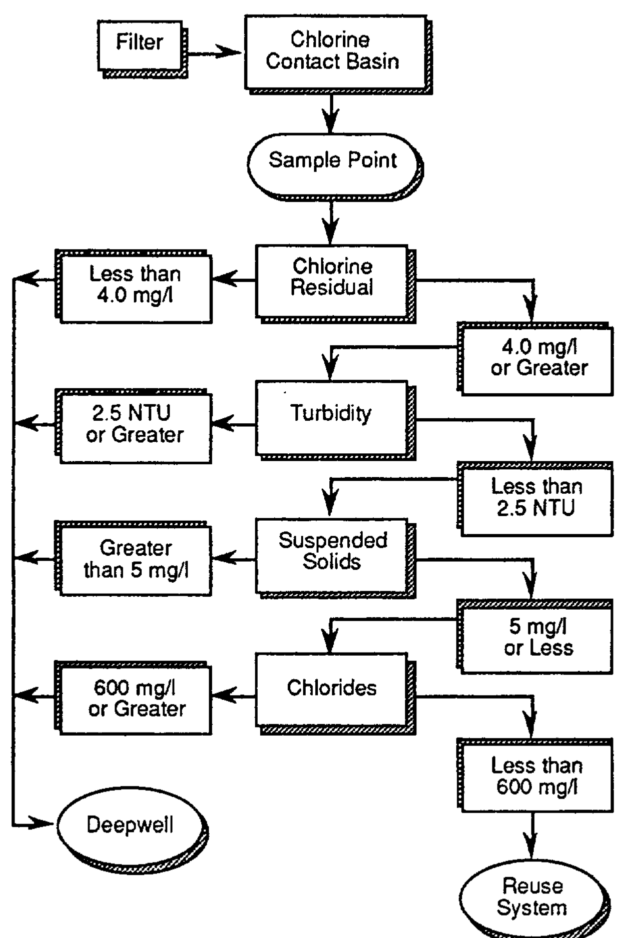
The dual distribution system comprises an extensive network of more than 260 mi (420 km) of pipe ranging in diameter from 2 to 48 in (5 to 122 cm). The system incorporates five city-owned and operated, and four privately-owned and operated booster pump stations. Operational storage is provided in covered storage tanks at the treatment facilities; however, no seasonal storage is provided. Instead, 10 deep wells inject excess reclaimed water into a saltwater aquifer approximately 1,000 ft (300 m) below the land surface. On a yearly average, approximately 60 percent of the reclaimed water produced is injected into the deep wells.

Criteria for delivery of reclaimed water to the system include chlorine residual, turbidity, SS, and chloride concentrations. Reclaimed water is rejected for reuse and diverted to the deep wells if the chlorine residual is less than 4.0 mg/L, turbidity exceeds 2.5 nephelometric turbidity units (NTU), SS exceed 5 mg/L rejected water, or chloride concentrations exceed 600 mg/L.

While the initial impetus for the reuse system was pollution abatement, its greatest benefit has been water conservation. By providing reclaimed water for urban irrigation and other nonpotable uses, St. Petersburg has been able to meet the community's rising potable water demands without increasing supplies, despite a 10 percent population growth. Since procuring additional potable supplies from an inland source would be prohibitively expensive, water reuse has also made economic sense for St. Petersburg.

Source: Johnson, 1990; CDM 1987.

City of St. Petersburg Reclaimed Water Delivery Criteria



Source: Johnson, 1990.

3.8.2 *Meeting Cooling Water Demands with Reclaimed Water: Palo Verde Nuclear Generating Station, Arizona*

The Palo Verde Nuclear Generating Station (PVNGS) is the largest nuclear power plant in the nation, with a generating capacity of 3,810 MW. The plant is located in the desert, approximately 55 mi (89 km) west of Phoenix, Arizona. The facility utilizes reclaimed water for cooling purposes, and has zero discharge. The sources of the cooling water for PVNGS are two wastewater treatment plants in Phoenix and Tolleson, which provide secondary treatment. The reclaimed water receives additional treatment at the power plant to meet water quality requirements.

PVNGS initially investigated alternative cooling systems in conjunction with the available sources of cooling water in the surrounding area. PVNGS first investigated once-through cooling and found that the high demand could not be met by any water bodies in the surrounding area. PVNGS then decided to utilize cooling towers which would only require an outside source to provide enough water lost through evaporation and for blowdown water to control salt content. This make-up demand of approximately 37,000 gpm (2,330 L/s), based on 75 percent annual average station capacity factor, still posed obstacles in locating a source of water that could meet this delivery rate and the quality requirements for coolant water.

The Colorado River, located 100 mi (160 km) to the west, was the first choice; however, the competition for the water from several states eliminated that alternative. Groundwater was also eliminated as an alternative due to quantity and quality concerns. It was then determined that of the 150 mgd (6,575 L/s) of secondary quality effluent being produced by the 91st Avenue WWTP in Phoenix, only 35 mgd (1,530 L/s) was committed to other users and the remaining 115 mgd (5,000 L/s) was being discharged to the normally dry Salt River. In addition, the Tolleson WWTP, located only 1 mile from the 91st Avenue plant, produced 17.5 mgd (767 L/s) of effluent that was also being discharged into the Salt River.

The combined available flow from the two plants, 132.5 mgd (5,800 L/s), was determined to more than adequately meet the PVNGS flow demand and was selected as the cooling water source. The transmission system from the WWTPs to PVNGS consists of 28 mi (45 km) of gravity pipeline, ranging from 114 in (290 cm) to 96 in (244 cm) in diameter, and 8 mi (13 km) of 66-in (168 cm) diameter pressurized force main.

Two 467-ac (189-ha) evaporation ponds were constructed to dispose of liquid waste from blowdown. The number of cycles of concentration was determined to be 15 without any scale formation, so long as the reclaimed water from the WWTP was further treated prior to use. A 90-mgd (3,940 L/s) tertiary wastewater reclamation facility (WRF) was constructed at PVNGS. The treatment process includes trickling filtration, cold lime/soda ash softening, and gravity filters.

The trickling filtration reduces influent ammonia, which causes metal corrosion, from 18-25 mg/L (As N) to less than 5 mg/L. The filters provided a second benefit of reducing alkalinity, thereby lowering the lime softening demand. Cold lime/soda ash softening reduces scaling and corrosive components such as calcium, magnesium, silica and phosphate. Lastly, gravity filters deliver a filtered effluent of less than 10 mg/L TSS.

3.8.3 *Agricultural Reuse in Tallahassee, Florida*

The Tallahassee agricultural reuse system is a cooperative operation in which the city owns and maintains the irrigation system, while the farm is leased to commercial enterprise. During evolution of the system since 1966, extensive evaluation and operational flexibility have been key factors in its success.

The City of Tallahassee was one of the first cities in Florida to utilize reclaimed water for agricultural purposes. Spray irrigation of reclaimed water from the City's secondary wastewater treatment plant was initiated in 1966.

Detailed studies of this system in 1971 showed that the system was successful in producing crops for agricultural use. The study also concluded that the soil was effective at removing SS, BOD, bacteria, and phosphorus from the reclaimed water.

Until 1980, the system was limited to irrigation of 120 ac (50 ha) of land used for hay production. Based upon success of the early studies and experience, a new sprayfield was constructed in 1980 southeast of Tallahassee.

The Southeast Sprayfield has been expanded twice since 1980 to a total area of approximately 1,750 ac (700 ha). The permitted application rate of the site is 3.16 in (8 cm)/week, for a total capacity of 21.5 mgd (942 L/s).

Sandy soils account for the high application rate. The soil composition is about 95 percent sand, with a clay layer at a depth of approximately 33 ft (10 m). The sprayfield has gently rolling topography with surface elevations ranging from 20 to 70 ft (6 to 21 m) above sea level.

Secondary treatment is provided the city's Thomas P. Smith wastewater renovation plant. The reclaimed water produced by this 17.5-mgd (767 L/s) activated sludge plant meets water quality requirements of 20 mg/L for BOD and TSS and 200/100 mL for fecal coliform.

Reclaimed water is pumped approximately 8.5 mi (13.7 km) from the treatment plant to the sprayfield and distributed via 13 center-pivot irrigation units.

The major crops produced include corn, soybeans, coastal bermuda grass, and rye. Corn is stored as high-moisture grain prior to sale, and soybeans are sold upon harvest. Both the rye and bermuda grass are grazed by cattle. Some of the bermuda grass is harvested as hay and haylage.

Sources: Payne *et al.*, 1989; Overman and Leseman, 1982.

3.8.4 *Seasonal Water Reuse Promotes Water Quality Protection: Sonoma County, California*

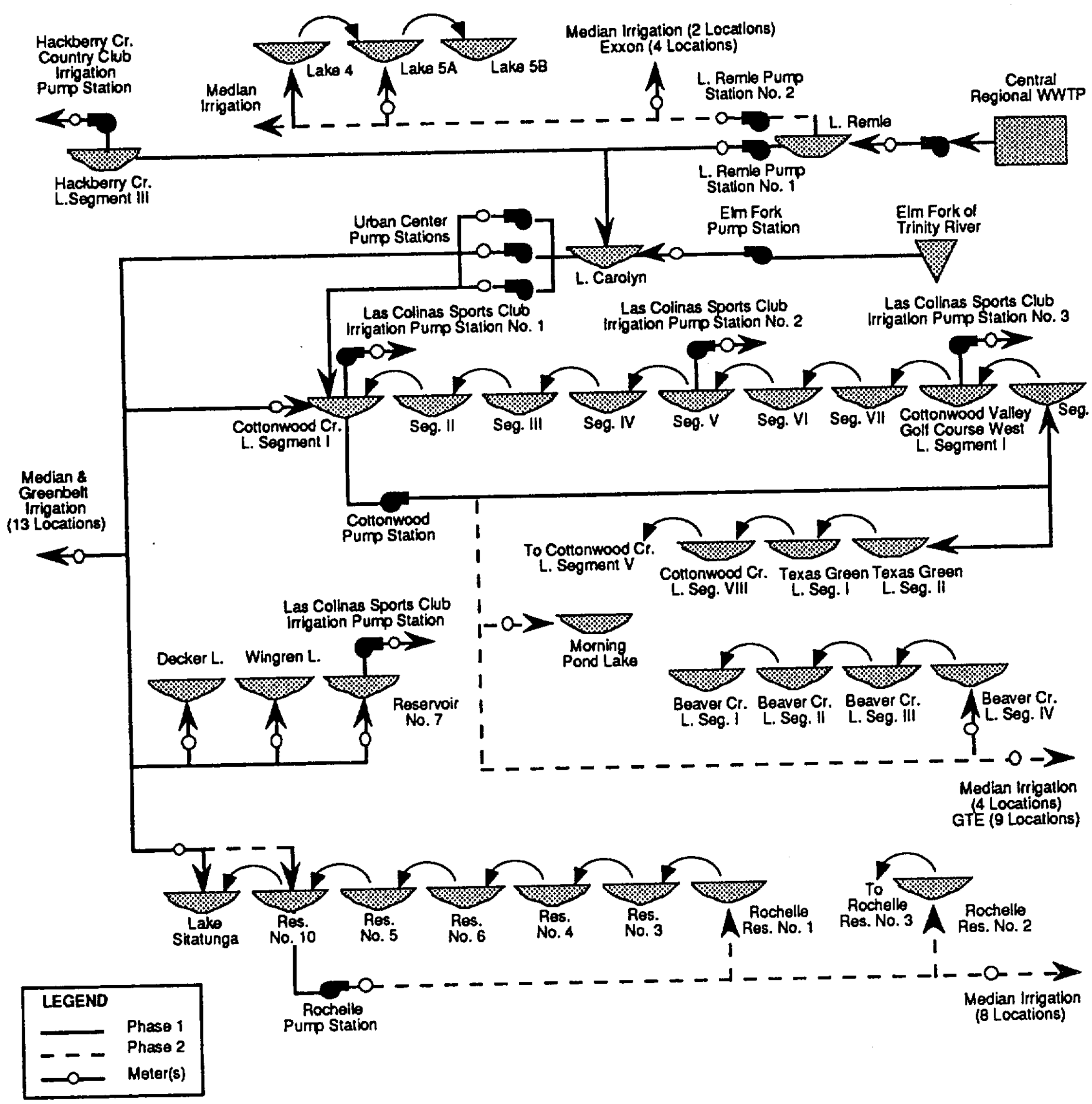
Faced with a "no discharge" requirement in accordance with the San Francisco Bay Regional Water Quality Control Board's 1982 Basin Plan, the Sonoma Valley County Sanitation District investigated the diversion of approximately 3 mgd (131 L/s) of effluent during the dry weather months of May through October. The receiving water, Schell Slough, is a tidal estuary less than 150 ft (46 m) wide and less than 10 ft (3 m) deep at high tide. The slough is particularly sensitive to water quality impacts during the dry season, from May to October, when fresh water flows in the slough cease and the water body becomes a dead end slough flushed only by limited tidal action. Dry weather dye studies indicated limited flushing in the dry season. Based on these studies, the "no discharge" directive for the district was modified to prohibit discharge only from May to October 31 of each year, with discharge allowed during the rainy season.

Instead of discharging to the slough during the dry season, local vineyards are irrigated with reclaimed water. While the nutrient content of reclaimed water is often viewed as a benefit, in this application there was a concern that the nitrogen would produce excessive foliage growth at the expense of grape production. As a condition of use, the farmers required denitrification of the reclaimed water. Nitrogen removal is achieved by denitrification on an overland flow field. Cheese whey is added to the reclaimed water prior to overland flow as a substitute for growth of the denitrification microorganisms. A backup means of avoiding discharge to Schell Slough between May and October has been developed for periods of high wastewater flows and/or low irrigation demands. Excess reclaimed water is spray irrigated and flows through a wetlands into Huderman slough. Huderman Slough has greater dilution flows than Schell Slough in dry weather, resulting in reduced impacts when and if a discharge is required.

3.8.5 *Combining Reclaimed Water and River Water for Irrigation and Lake Augmentation: Las Colinas, Texas*

Advanced secondary treated effluent and raw water from the Elm Fork of the Trinity River are used to irrigate golf courses, medians and greenbelt areas, and to maintain water levels at the Las Colinas development in Irving, Texas. Las Colinas is a 12,000-ac (4,800 ha) master planned development that features exclusive residential areas, high-rise offices, luxury hotels, and four championship golf courses. The drought-proof supply of reclaimed water and river water, known as the Raw Water Supply Project (RWSP), delivers irrigation water to 550 ac (220 ha) of landscaped areas and provides water to 19 lakes to make up evaporative losses from their 270-ac (110 ha) total surface area.

Schematic of the Las Colinas Raw Water Supply Project



The RWSP was initiated in July 1987. The reclaimed water originates from the 115-mgd (5,040 L/s) Central Regional wastewater treatment plant (CRWWTP). Reclaimed water is available year-round but is limited to the pumping system's capacity of 16.4 mgd (719 L/s). Reclaimed water is pumped 11 mi (18 km) through a 30-in (76-cm) diameter pipeline to Lake Remle. A portion of the water is then pumped to a storage lake for irrigation at one country club, and a portion is pumped to Lake Carolyn where it is mixed with river water. A pump station on the Elm Fork can deliver up to 4.6 mgd (202 L/s) of river water through a 16-in (41-cm) diameter pipeline to Lake Carolyn. All water from the Elm Fork and the CRWWTP blends with water in at least one lake before distribution to 23 discharge points. The lakes are designed to allow water to spill from lake to lake within the development thereby controlling water surface elevations and enhancing circulation. A schematic of the distribution system is presented below.

Treatment processes at the CRWWTP consist of primary clarification, equalization, activated sludge, secondary clarification, filtration, activated carbon (as needed), and disinfection by chlorination. The reclaimed water discharged into Lake Remle has consistently met discharge permit requirements of no more than 10 mg/L BOD and 15 mg/L TSS. In addition, water quality samples are collected from the Elm Fork and at selected lakes to assess the water's irrigation, aesthetic, and recreational quality.

The parameters monitored include BOD, TSS, fecal coliform, dissolved oxygen, Secchi depth, pH, sodium adsorption ratio (SAR), salinity, ortho-phosphorus, and algae. Mixing the reclaimed water with river water in lakes reduces the SAR value of the reclaimed water from 3.85 to less than 2.0 in Lake Carolyn. A SAR value of 3.0 was established as an acceptable limit to irrigate golf courses at Las Colinas. The concentration of ortho-phosphorus has increased at sampling locations in Lake Remle and Lake Carolyn since the RWSP began. However, accelerated eutrophication of lakes has not been noticed, and the lake maintenance program for aquatic weeds and algae was not altered.

Six fountain aerators were installed in lakes to increase their assimilative capacity and to improve lake appearance. In general, water quality in the Las Colinas lakes remains acceptable subsequent to delivery of reclaimed water. The success of the program is attributed to the excellent quality of the reclaimed water; the significant dilution which occurs as the reclaimed water, river water and natural drainage blend during progression through the system; and the flexibility to manage the system by blending waters and promoting circulation through the lakes, as required, to maintain water quality.

Sources: Water Pollution Control Federation, 1989; Smith *et al.*, 1990.

3.8.6 *Integrating Wetlands Application with Urban Reuse: Hilton Head Island, South Carolina*

Hilton Head Island, located off the southeastern shore of South Carolina, is plagued by poor soil conditions and saltwater intrusion. The island is resort-oriented with several golf courses and a booming population. Because of the soil conditions and the increasing population, wastewater treatment and effluent disposal have become an increasing concern.

In 1982, a wastewater management plan was developed with the goal of maximizing water reuse on the island. In 1983, the Hilton Head Island Utility Committee was created to coordinate the efforts of the various agencies involved in implementing the plan. The island-wide plan called for upgrading all wastewater treatment plants to tertiary treatment in order to minimize nutrient concentrations in the reclaimed water and allow for discharge when reuse demand is not sufficient. The treatment levels can remain at the advanced secondary treatment levels for golf course irrigation. In addition to managing and coordinating the island-wide wastewater treatment and reuse program, the Hilton Head Island Utility Committee also developed guidelines for reuse. These guidelines contain information regarding the approved uses of reclaimed water, design criteria, and administrative and hook-up procedures.

Golf courses have been irrigated with reclaimed water on Hilton Head Island since 1973, when the Sea Pines and Forest Beach Public Service Districts began irrigating the Club Course at Sea Pines Plantation. In 1985, the Sea Pines Public Service District upgraded and expanded the existing wastewater treatment plant to 5 mgd (219 L/s).

The reclaimed water transmission system was also to be upgraded and expanded in two phases. The Phase I expansion includes service to approximately 150 ac (60 ha) of commercial and multi-family residences in addition to the existing and new golf course irrigation. The entire system, once completed, will include approximately 13 linear mi (20 km) of new reuse piping.

To serve the expanded irrigation system, a new 10-mgd (438 L/s) effluent pumping station has been constructed, but is not yet fully operational. In addition, a 5-million gal (19-million L) storage tank has been constructed.

Because the demand for reclaimed water decreases during the rainy season, an alternative disposal system is required. Several alternatives were studied, with the most environmentally sound being the use of existing wetlands on the island.

The use of reclaimed water to supplement wetlands systems is ideal. The demand for reuse among the connected customers decreases in the wet winter months and increases in the summer. Due to the natural cycling, wetlands typically are drier in the summer and wet in the winter. This is the exact opposite of the reuse demand and makes a perfect complement to the irrigation system.

Boggy Gut wetland in the Sea Pines Forest Preserve was selected for a 3-year pilot study beginning in 1983. The study called for an increase in the discharge from 0.3 mgd (13 L/s) to 1.0 mgd (44 L/s) over the entire study period. No observable detrimental impacts on groundwater were noted, and the pilot study was deemed a success. It has since become fully operational.

The Sea Pines Public Service District Wetlands Program has been expanded to include the White Ibis Marsh, which recently began to receive reclaimed water. The conceptual plan is to enhance the performance of both wetland cells by stopping service to one cell every 5 years and allowing the built up organics to oxidize. Service will once again be returned to the renewed cell and the same process repeated for the next cell.

The second project of interest is the Hilton Head Plantation treatment plant and reuse system, located in the northern portion of the island. The AWT plant serves a private residential area, with golf course irrigation as the primary means of reuse. The wet weather back-up to the system is discharge to two wetlands: the Whooping Crane Conservancy and the Cypress Conservancy.

Prior to wet weather discharge, both of these wetlands areas had been drying due to changes in water flow patterns resulting from development in the area. The Nature Conservancy worked with the Hilton Head Plantation in an effort to mutually benefit both institutions. Hilton Head Plantation was granted a wet weather discharge back-up to the golf course irrigation system, and the Whooping Crane and Cypress conservancies were given much needed water to help restore their natural flow patterns.

Since wet weather discharge has begun to these two wetlands areas, there has been a revival of wildlife. Wading birds have increased in the conservancies, and they are once again in their rookery states.

Both of these projects on Hilton Head Island are using reclaimed water for recreational benefit by golf course irrigation and are providing enhancement to area wetlands by wet weather discharge.

Source: Hirsekorn and Ellison, 1987.

3.8.7 *Groundwater Replenishment with Reclaimed Water: Los Angeles County, California*

In south-central Los Angeles County, replenishment of groundwater basins is accomplished by artificial recharge of aquifers in the Montebello Forebay area. Waters used for recharge via surface spreading include local storm runoff, imported water from the Colorado River and state project, and reclaimed water. The latter has been used as a source of replenishment water since 1962. At that time, approximately 12,000 ac-ft/yr (15 x 10^6 m^3/yr) of disinfected, activated sludge secondary effluent from the Sanitation Districts of Los Angeles County Whittier Narrows water reclamation plant (WRP) was spread in the Montebello Forebay area of the Central groundwater basin, which has an estimated usable storage capacity of 780,000 ac-ft (960 x 10^6 m^3). In 1973, the San Jose Creek WRP was placed in service and also supplied secondary effluent for recharge. In addition, effluent from the Pomona WRP that is not reused for other purposes is discharged into San Jose Creek, a tributary of the San Gabriel River, and ultimately becomes a source for recharge in the Montebello Forebay.

In 1978, all three reclamation plants were upgraded to provide secondary treatment, dual-media filtration (Whittier Narrows and San Jose Creek WRPs) or activated carbon filtration (Pomona WRP), and chlorination/ dechlorination. In 1990, 50,000 ac-ft (62 x 10^6 m^3/yr.)of reclaimed water was recharged, or approximately 30 percent of the total inflow to the Montebello Forebay.

The replenishment program is operated by the Los Angeles County Department of Public Works (DPW), while overall management of the groundwater basin is administered by the Central and West Basin Water Replenishment District. DPW has constructed two spreading areas designed to increase the indigenous percolation capacity. The Rio Hondo spreading basins have a total of 427 ac (173 ha) available for spreading, and the San Gabriel River spreading grounds have 224 ac (91 ha). The Rio Hondo and San Gabriel River spreading grounds are subdivided into individual basins that range in size from 4 to 20 ac (1.5 to 8 ha).

Under normal operating conditions, batteries of the basins are rotated through a 21-day cycle consisting of:

- A 7-day flooding period during which the basins are filled to maintain a constant 1.2-m (4-ft) depth;
- A 7-day draining period during which the flow to the basins is terminated and the basins are allowed to drain; and
- A 7-day drying period during which the basins are allowed to thoroughly dry out.

This wetting/drying operation serves several purposes, including maintenance of aerobic conditions in the upper soil strata and vector control in the basins.

The reclaimed water produced by each reclamation plant complies with primary drinking water standards and meets total coliform and turbidity requirements of less than 2.2/100 mL and 2 NTU, respectively. Reclaimed water and groundwater quality data are given in the following table.

1988-1989 Results of Reclaimed Water Analyses for the Montebello Forebay Groundwater Recharge Project[a]

Constituent	San Jose WRP[b]	Whittier Narrows WRP	Pomona WRP	Discharge Limits
Arsenic (mg/L)	0.005	0.004	<0.004	0.05
Aluminum (mg/L)	<0.06	<0.10	<0.08	1.0
Barium (mg/L)	0.06	0.04	0.04	1.0
Cadmium (mg/L)	ND[c]	ND	ND	0.01
Chromium (mg/L)	<0.02	<0.05	<0.03	0.05
Lead (mg/L)	ND	ND	<0.05	0.05
Manganese (mg/L)	<0.02	<0.01	<0.01	0.05
Mercury (mg/L)	<0.0003	ND	<0.0001	0.002
Selenium (mg/L)	<0.001	0.007	<0.004	0.01
Silver (mg/L)	<0.005	ND	<0.005	0.05
Lindane (ug/L)	0.05	0.07	<0.03	4
Endrin(ug/L)	ND	ND	ND	0.2
Toxapene (ug/L)	ND	ND	ND	5
Methoxyclor (ug/L)	ND	ND	ND	100
2,4-D(ug/L)	ND	ND	ND	100
2,3,5-TP (ug/L)	<0.11	ND	ND	10
SS (mg/L)	<3	<2	<1	15
BOD (mg/L)	7	4	4	20
Turbidity (TU)	1.6	.1.6	1.0	2
Total Coliform (#/100 mL)	<1	<1	<1	2.2
TDS (mg/L)	598	523	552	700
Nitrite + Nitrate (mg/L)	1.55	2.19	0.69	10
Chloride (mg/L)	123	83	121	250
Sulfate (mg/L)	108	105	82	250
Fluoride (mg/L)	0.57	0.74	0.50	1.6

[a] Average of samples collected from October 1988 through September 1989. Sampling frequency varied from daily to bimonthly depending on constituent.
[b] WRP - Water reclamation plant
[c] ND - Not detected.

Source: Sanitation Districts of Los Angeles County, 1989.

3.8.8 *Aquifer Recharge Using Injection of Reclaimed Water: El Paso, Texas*

El Paso, Texas has injected reclaimed wastewater from the Fred Hervey water reclamation plant into the Hueco Bolson aquifer since June 1985. The Hueco Bolson aquifer is an unconfined aquifer that supplies about 65 percent of the water supply needs of El Paso. The reclaimed water is transported from the treatment plant 1 mile (1.6 km) to a 3-mile (4.8 km) long series of 10 injection wells. Each well is 16-in (41 cm) diameter and is screened from about 350 ft (107 m) deep to a completed depth of 800 ft (244 m) below ground.

The Hueco Bolson aquifer recharge was selected as a demonstration study for the High Plains Reuse Project. The 4-year study, slated to be completed by October 1992, is sponsored by the U.S. Bureau of Reclamation, El Paso Water Utility, and the U.S. Geological Survey. The study investigates the impacts of using reclaimed water to recharge a water supply aquifer and evaluates effectiveness and reliability of treatment processes in the plant.

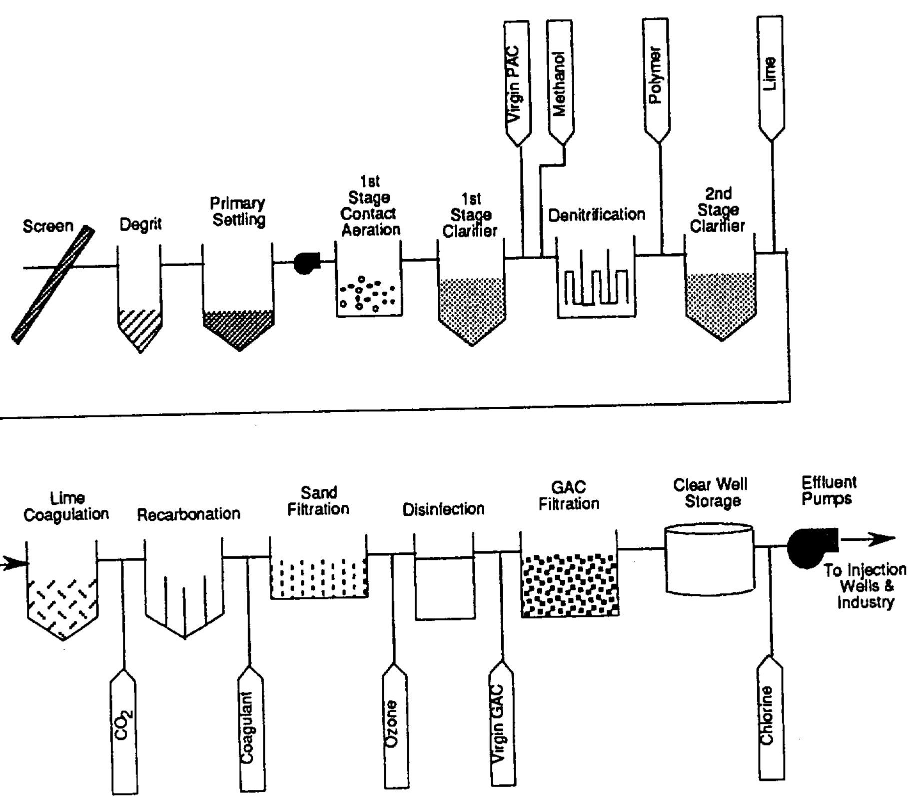
As part of the study, a groundwater flow and solute transport model was used to calculate the residence time of injected reclaimed water in the aquifer before it is pumped out at production wells located from 0.25 mi (0.4 km) to 4.5 mi (7.2 km) distant from the injection wells. The model results indicate that the representative residence time is approximately 5 to 15 years.

The reclaimed water must meet drinking water standards before it is injected to the aquifer. The effluent maintains a free chlorine residual of about 0.3 mg/L as it leaves the treatment train. The chlorine residual is needed to prevent bacterial growth in the storage tank before the reclaimed water is injected. The concentrations of trihalomethanes (THMs) in the effluent is less than 50 ug/L (microgram per liter). Groundwater samples collected from monitor wells near the injection site have had elevated concentrations of THMs, but always less than 30 ug/L.

The demonstration study includes a full evaluation of the reliability of the water reclamation plant and identification of the role played by each treatment step in achieving the drinking water quality objectives established for the effluent. The plant reliability review involves analyses of priority pollutants and THMs in water samples taken from the treatment train, THM-precursor analysis at the granular activated carbon and ozonation treatment stages, and evaluations of biotoxicity and pathogen removal.

The Fred Hervey Water Reclamation Plant has a maximum capacity of about 12 mgd (526 L/s). Its 10-step treatment train begins with primary treatment to allow

Liquid Treatment Train for Groundwater Recharge, El Paso, Texas



screening, degritting, sedimentation and flow equalization. The primary effluent enters a two-stage biophysical process which combines activated sludge with powdered activated carbon adsorption (PACT™ system). This step of the treatment is designed for organic removal, nitrification and denitrification. Methanol is added to the second stage to provide a carbon source for the denitrifiers. Waste secondary sludge and spent carbon are processed in a wet air regeneration (oxidation) unit which destroys the sludge and regenerates the carbon for reuse in the PACT system. The wastewater effluent advances to a lime treatment step to remove phosphorus and heavy metals, to kill viruses, and to soften the effluent. Turbidity removal is provided by sand filters and disinfection is provided by ozonation. The final product water is passed through a granular activated carbon filter to provide final polishing before release to storage.

Between 1985 and 1990, approximately 7.5 billion gal (28 x 10^6 m^3) of reclaimed water have been injected to recharge the Hueco Bolson aquifers. The current price of treating and injecting the water is about $2.00/gal (up from $1.55/1,000 gal in 1986).

Before the aquifer recharge project was initiated, water levels in the Hueco Bolson aquifer declined at a rate of 2 to 6 ft (0.6 to 1.8 m)/yr because groundwater was withdrawn 20 times faster than the aquifer's natural rate of recharge. Groundwater model results indicate that groundwater levels in 1990 are 8 to 10 ft (2.4 to 3.0 m) higher than what they would have been without the aquifer recharge project.

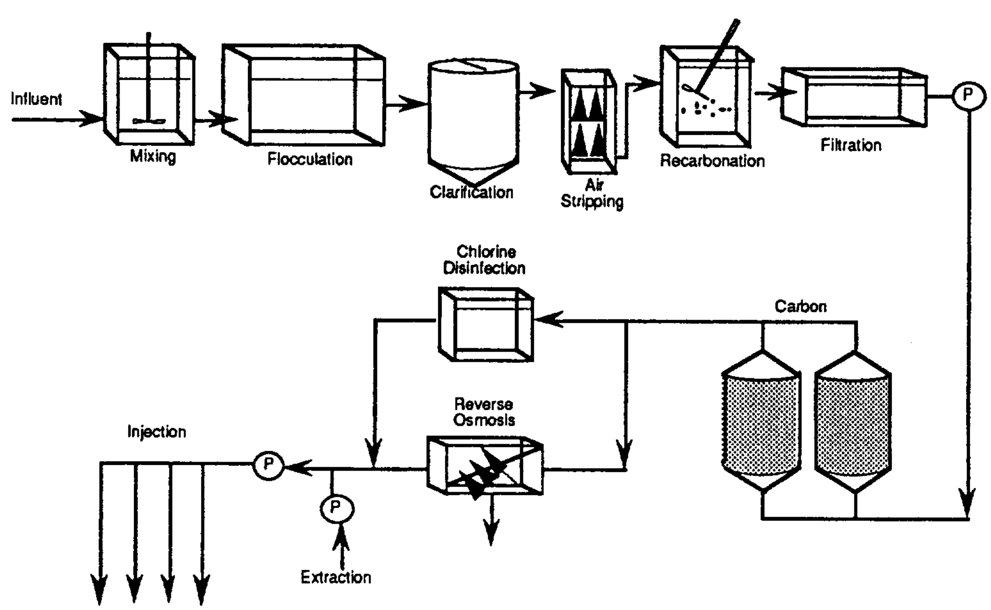
Sources: Knorr, 1985, Knorr *et al.*, 1987.

3.8.9 Water Factory 21 Direct Injection Project: Orange County, California

A project involving groundwater recharge by the injection of reclaimed water is operated by the Orange County Water District (OCWD) in Fountain Valley, California. OCWD first began pilot studies in 1965 to determine the feasibility of using tertiary wastewater treatment in a hydraulic barrier system to prevent saltwater encroachment into potable water supply aquifers. Construction of a tertiary treatment facility, known as Water Factory 21, was started in 1972, and injection operations began in 1976.

Water Factory 21 has a design capacity of 15 mgd (657 L/s) and treats activated sludge secondary effluent from the adjacent Orange County Sanitation District's (OCSD) wastewater treatment plant by the following unit operations: lime clarification for removal of SS, heavy metals, and dissolved minerals; air stripping (not currently in service) for removal of ammonia and volatile organic

Water Factory 21 Treatment Processes



Source: Adapted from Water Pollution Control Federation, 1989.

compounds; recarbonation for pH control; mixed-media filtration for removal of SS; granular activated carbon adsorption for removal of dissolved organics; reverse osmosis (RO) for demineralization; and chlorination for biological control and disinfection.

Due to a total dissolved solids limitation of 500 mg/L prior to injection, RO is used to demineralize up to 5 mgd (219 L/s) of the reclaimed water used for injection. The feedwater to the RO plant is effluent from the mixed-media filters. Effluent from the carbon adsorption process is disinfected and blended with RO-treated water. Activated carbon is regenerated onsite. Solids from the settling basins are incinerated in a multiple-hearth furnace from which lime is recovered and reused in the chemical clarifier. Brine from the RO plant is pumped to OCSD's facilities for ocean disposal.

Reclaimed water produced at Water Factory 21 is injected into a series of 23 multi-casing wells, providing 81 individual injection points into four aquifers to form a seawater intrusion barrier known as the Talbert injection barrier (Argo and Cline, 1985). The injection wells are located approximately 3.5 mi (5.6 km) inland from the Pacific Ocean. There are seven extraction wells (not currently being used) located between the injection wells and the coast. Before injection, the product water is blended 2:1 with well water from a deep aquifer not subject to contamination. Depending on basin conditions, the injected water flows toward the ocean forming a seawater barrier, flows inland to augment the potable groundwater supply, or flows in both directions.

Water Factory 21 reliably produces high-quality water. No coliform organisms were detected in any of 179 samples of the reclaimed water during 1988. A virus monitoring program conducted from 1975 to 1982 demonstrated to the satisfaction of the state and county health agencies that Water Factory 21 produces reclaimed water that is essentially free of measurable levels of viruses (McCarty et. al., 1982). The average turbidity of filter effluent was 0.22 FTU and did not exceed 1.0 FTU during 1988.

The average COD and TOC concentrations for 1988 were 8 mg/L and 2.6 mg/L, respectively. The effectiveness of Water Factory 21's treatment processes for the removal of inorganic and organic constituents is shown in the following tables.

Water Factory 21 Injection Water Quality

Constituent	Discharge Limits	Injection Water*
Concentration in mg/L		
Sodium	115	82
Sulfate	125	56
Chloride	120	84
TDS	500	306
Hardness	180	60
pH (units)	6.5-8.5	7.0
Ammonia Nitrogen	—	4-7
Nitrate Nitrogen	—	0.4
Total Nitrogen	10	5.8
Boron	.05	0.4
Cyanide	0.2	<0.01
Fluoride	1.0	0.5
MBAs	0.5	0.5
Concentration in ug/L		
Arsenic	50	<5.0
Barium	1,000	18
Cadmium	10	0.6
Chromium	50	<1.0
Cobalt	200	<1.0
Copper	1,000	4.7
Iron	300	33
Lead	50	<1.0
Manganese	50	4.3
Mercury	2	<0.5
Selenium	10	<5.0
Silver	50	3.3

*After blending 2:1 with deep well water.

Source: Wesner, 1989.

Water Compounds Detected In Water Factory 21 Injection Water[a]

Constituent	Injection Water [b] (ug/L)
Methylene Chloride	1.0
Chloroform	5.4
Dibromochloromethane	1.1
Chlorobenzene	TR[c]
Bromodichloromethane	3.7
Bromoform	0.8
1,1,1-Trichlorethane	TR

a Fifty-three specific volatile organic compounds were reported as undetected in the sample.
b After blending 2:1 with deep well water.
c TR = Trace. Concentration was below reportable detection limit.

Source: Orange County Water District, 1989.

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5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650

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